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TAJUK PROJEK : Investigation of failure modes in unreinforced brick masonry walls subjected to different load combination

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Abstract

The aim of this investigation is to study the mechanical behavior of structural clay brick masonry made from local materials and to investigate the effects of mortar joint thickness on the compressive strength of brickwork. Different sets of prisms, both full scale and half scale made from five bricks, and having different mortar joint thickness have been tested. Using a simple statistical method, the characteristic compressive strength of the structural brickwork under axial compression for each set has been determined. An attempt has also been made to assess the modulus of elasticity of the brick masonry. Numerical analyses of the prisms having different mortar joint thickness have also been carried out. Finite element analysis is carried out adopting two different idealization techniques, which assume the prisms are made from a homogenous material in the first assumption and from composite material in the second assumption. In conclusion the effect of the mortar joint thickness on the compressive strength of the masonry has been reported, and an approximate modulus of elasticity of the brickworks for analysis and design has been proposed. A minimum magnification factor has been proposed to predict the actual/experimental strength of the brick masonry from its finite element analysis.

Abstrak

Tujuan kajian ini adalah untuk mengkaji sifat mekanikal batu batan struktur tanah liat tempatan dan mengkaji kesan ketebalan sambungan motar ke atas kekuatan mampatan kerja bata. Beberapa set prisma, untuk kedua-dua skala penuh dan separuh yang diperbuat daripada lima bata, dengan ketebalan sambungan motar yang berbeza telah diuji. Menggunakan kaedah statistik mudah,ciri-ciri kekuatan mampatan batu bata struktur dengan mampatan paksi, untuk setiap set telah ditentukan.Kajian juga telah dijalankan untuk menilai modulus keanjalan batu bata. Analisis numerical untuk prisma dengan ketebalan sambungan motar telah dijalankan. Analisis usul tidak sehingga dijalankan menggunakan dua teknik 'idealization' yang berbeza iaitu dengan anggapan prisma dibuat menggunakan bahan 'homogenous' untuk anggapan pertama dan menggunakan bahan komposit untuk anggapan kedua. Kesimpulannya kesan ketebalan sambungan motar ke atas kekuatan mampatan batu bata telah dilaporkan, dan anggaran modulus keanjalan kerja bata untuk analisis dan rekabentuk telah dicadangkan. Faktor minimum maknifikasi adalah dicadangkan untuk menganggarkan kekuatan sebenar/ujikaji batu bata telah analisis unsur tidak terhingga.

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INVESTIGATION OF FAILURE MODES IN UNREINFORCED BRICK MASONRY WALLS SUBJECTED TO DIFFERENT LOAD COMBINATIONS

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TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
I	INTRODUCTIN	5
	1.0 Introduction to brick masonry	5
	1.1 Objectives	5
	1.2 Scope of work	5
	1.3 Background of thr problem	5
II	LITERATURE REVIEW	7
	2.0 Introduction	7
	2.1 Unreinforced masonry	7
	2.2 Axial compression	7
	2.3 Standard prism test	8
	2.4 Design consideration in load bearing brickwork	8
	2.5 Construction materials	8
	2.5.1 Clay bricks	8
	2.5.2 Mortar	8
	2.6 Foundation Systems	8
	2.7 Advantages of the load bearing brickwork	9
	2.7.1 Safety	9
	2.7.2 Economy	9
	2.7.3 Construction time	9
	2.7.4 Appearance and durability	9
III	METHODOLOGY	10
	3.0 EXPERIMENTAL STUDY	10
	3.1 Selection and testing of materials for the models	10
	3.1.1 Full size clay brick	10
	3.1.2 Small size clay bricks	12
	3.1.3 Mortar designation	13
	3.1.4 Construction & testing of the models & their results	13
	3.1.4.1 Full scale prisms	13
	3.1.4.2 Half scale prisms	14
	3.1.5 Modulus of elasticity	16
	3.2 NUMERICAL ANALYSIS	16
	3.2.1 Idealization of models as a homogenized material	17
	3.2.2 Idealization of models as a composite materials	18

IV	COMPARISON AND DISCUSSION OF RESULTS	20
	4.1 Experimental results	20
	4.2 Results of numerical analysis	21
V	CONCLUSIONS AND RECOMMENDATIONS	27
	Acknowledgment	28
	References	28

APPENDICES (Research papers published)

(a) Load bearing brickwork method in building industries, Industrialized building systems, Sept. 2000, Kuala Lumpur, Malaysia.

(b) Mechanical behaviour of structural brick masonry: An experimental evaluation, 5th Asia-Pacific Structural Engineering and Construction Conference, 26-28 Aug. 2003, Johor Bahru, Malaysia.

(c) Finite element modeling of structural clay brick masonry subjected to axial compression. Jurnal Teknologi, UTM, 41(B), Dec. 2003.

CHAPTER I

INTRODUCTION

1.0 Introduction to brick masonry

Brick masonry is probably the oldest building material that still finds wide use in today's building industries. It is well known that brickwork forms an attractive cladding and it is durable material with good thermal and acoustic and excellent fire resistance. What is not so well known is that it is an economic structural material that can be used to build faster and cheaper buildings compared to other construction materials. Therefore the usage of brick masonry in building construction is an economic faster and simple technique for producing durable and attractive structure. Load bearing construction is still the preferred method for housing through out Europe, America, Australia, new Zealand, China and in most part of Asia and about 70% of the world population live in load bearing houses. However, this method of construction has yet to be effectively applied in Malaysia.

1.1 Objectives

1) To investigate the structural behavior of unreinforced masonry made from local materials subjected to axial compressive loads.

2) To determine the effect of mortar joint thickness on the compressive strength of clay brick masonry

1.2 Scope of work

1) Testing of full scale and half scale prism models having different mortar joint thickness under axial compressive load.

2) To carry out finite element analysis of full scale models having different mortar joint thickness subjected to axial compression.

1.3 Background of the problem

The unreinforced brickwork is not only attractive cladding with good thermal and acoustic insulation and excellent fire resistance but also a good structural material, which can be used to construct faster and cheaper buildings. The load bearing brickwork method in building industry has yet to be effectively applied in Malaysia.

Load bearing brickwork construction is most appropriately used in buildings, which have larger number of rooms relatively small to medium sizes. The load from the structural masonry will be more uniformly distributed at foundation level, which will cause to an economical foundation system.

The usage of brick masonry and flat slab floor system in this type of construction will eliminate beams and columns and their formwork.

The current technology available in the industry is on the basis of practices used in western countries specifically U.K., which have different climatic, cultural and soil condition.

Investigation is needed to study the behavior of brick masonry subjected to axial compressive load using experimental and finite element analysis. The research finding is expected to gain the confidence of practicing design engineers in Malaysia.

CHAPTER II
LITERATURE REVIEW

2.0 Introduction

Structural design in masonry requires a clear understanding of the behavior of the composite materials (unit + mortar) under various stress conditions. Primarily structural masonry walls are vertical load bearing elements to carry gravity loads. However, walls are frequently required to resist horizontal shear forces or lateral pressure from earthquake, wind and earth pressure therefore, the strength of masonry in shear and in tension must also be considered. Various researchers such as Handry et al [11,12] and Drysdale et al [9] have carried out extensive research on brick masonry. Current value for the design strength of masonry has been derived on an empirical basis from wall, prisms and piers tests. Whilst this has resulted in safe designs, it gives very little insight into the behavior of the material under various loads. Therefore, investigation is needed to study the behaviour of brick masonry made from local materials.

2.1 Unreinforced masonry

Unreinforced masonry elements are the simplest to construct as they contain no reinforcement other then possible inclusion of light joint reinforcement to control shrinkage cracking and movement. Therefore it relies on the compressive strength of the masonry alone to resist the applied loads. Because masonry is strong in compression but weak in tension, therefore, unreinforced masonry has great resistance to loads causing compressive stresses.

2.2 Axial compression

With the modern use of high strength materials and thinner elements, compressive strength is often of prime importance in load bearing structures. Compression tests of masonry prisms are used as the basis for assigning design stress and in some cases, as quality control measures. Its importance has made prism compressive behavior a major research focus and potential correlations with other strength characteristics have been investigated. Test machine capacity and specimen height limits as well as other practical consideration have led to use of prisms as the main type of compression test specimen rather then full-scale specimen.

2.3 Standard prisms test

BS 5628 describes test equipment, test procedure and reporting for prisms test. The standard prisms is usually one masonry unit long, one unit thick and can be build to be of various heights.

2.4 Design consideration in load bearing brickwork

Load bearing brickwork method is most appropriately used for buildings in which the floor areas are subdivided into a relatively large number of rooms of small to medium size and in which the floor plan is repeated on each story throughout the height of the building. These considerations give ample of opportunity for disposing load-bearing walls, continuous from foundation to roof level, and because of the moderate floor span, not called upon to carry unduly heavy concentration of vertical loads. The types of buildings, which are compatible with these requirements, include flats, hostels, hotels and other residential buildings. Stair walls, lift shafts, and service ducts play an important part in deciding layout and are often of preliminary importance in providing lateral rigidity. From the structural design point of view the load bearing brickwork walls have to support all the superstructure loads such as roof, walls and floor slabs and the lateral loads such as wind and soil pressure. The masonry construction differs from the conventional RC method, where beams and columns support the loads while in masonry the walls acts as structural element which provide support and stability for the building.

2.5 Construction material

2.5.1 Clay bricks

Structural masonry can be constructed using clay bricks and cement sand blocks. BS 5628: Part 1: 1992 specifies the minimum strength of 5 N/mm^2 and 2.8N/mm^2 for bricks and blocks respectively for the use in unreinforced masonry. The recommended standard size of brick is 215 x 105.2 x 65 mm with maximum tolerance of 7mm.

2.5.2 Mortar

Mortar is the second component in brickwork which for load bearing brickwork should be a mix of cement, lime, and sand. The proportion varies on the basis of strength requirement. The thickness of the mortar joint is normally about 10 to 12 mm. Lime is added to cement mortar to improve the workability, water retention and bonding properties. Depending on conditions and requirements, cement-sand mortar and cement sand plasticizer mortar are also specified by BS 5628: Part –3.

2.6 Foundation System

The load from structural masonry form tends to be more uniformly distributed and therefore, at foundation level, there is less need to spread the load to reduce the bearing pressure. This makes for economies, where strip, pad or raft footings are employed. A very unfavorable soil condition, may necessitate piling with ground beams.

2.7 Advantages of the load bearing brickwork

2.7.1 Safety
Incorporating all the safety factors recommended by the British codes of practice including BS: 5628 part 1, 2 & 3, the factor of safety in load bearing brickwork will be almost double of that of reinforced concrete construction.

2.7.2 Economy
The cost saving from the usage of load bearing brickwork system will range from 10% to 20% of the total cost of the building if compared with the conventional reinforced concrete construction.

2.7.3 Construction time
Compared to the conventional method, the clay brick masonry will save 10% to 30% of the construction time

2.7.4 Appearance and durability
Brick masonry is well proven building material possessing excellent properties in terms of appearance, durability, good thermal and acoustic insulation and better fire resistance. If constructed as exposed brick walls, it will eliminate fungus growth, peeling paint and enhances aestheticism and reduces maintenance costs.

CHAPTER III

METHODOLOGY

3.0 EXPERIMENTAL STUDY

The purpose of this investigation is to study the mechanical behavior of structural brickwork with particular reference to Malaysian condition. In the initial part of the study, experimental investigation has been carried out to study the effects of mortar joint thickness on the compressive strength of masonry, and an attempt has also been made to determine the approximate modulus of elasticity for the tested models.

The models include both full size prisms and half size prisms. In the case of full size prisms, the models are constructed using five standard size local bricks. For the construction of half scale prisms, a standard size brick has been cut into eight equal size pieces and the models have been constructed using five bricks.

3.1 Selection and Testing of Materials for the Models

3.1.1 Full size clay bricks

Ten full size clay bricks were selected randomly from the same batch of bricks which were used in the construction of the prisms. These bricks were tested to determine their compressive strength under axial compressive load. Table 1 shows the maximum compressive strength of the bricks.

The variability in strength of bricks for any particular batch is quite considerable. This makes it important to use a statistical method in evaluating their mean strength[6],[12]. The characteristic compressive strength of the tested bricks has been calculated using the following formulas and generated data in Table 2

$$f_k = \bar{x} - 1.64\sigma \qquad (1)$$

$$x_o = \frac{\sum x_i}{n_i} \qquad (2)$$

$$\bar{x} = x_o + w\left(\frac{\sum F_i D_i}{\sum F_i}\right) \qquad (3)$$

$$\sigma = w\sqrt{\frac{\sum F_i D_i^2 - (\sum F_i D_i)^2 / \sum F_i}{\sum F_i - 1}} \qquad (4)$$

where, x_o = average compressive strength of specimens

$\bar{x}$ = mean

w = width of the class interval, selected as 2.0 N/mm^2

n = number of models tested

σ = standard deviation

F_i = number of observations falling in the i^{th} class interval

D_i = deviation

Table 1 Compressive strength of tested clay bricks

No.	Brick size l x w x h (mm)	Maximum load (kN)	Compressive strength (N/mm^2)
1	206 x 90 x 66	505	27.24
2	214 x 91 x 67	360	18.49
3	212 x 91 x 66	379	19.65
4	206 x 91 x 67	428	22.83
5	217 x 94 x 66	452	22.16
6	217 x 94 x 66	473	23.19
7	209.5 x 89 x 67	605	32.50
8	214 x 93 x 66	423	21.25
9	204 x 87 x 66	639	35.74
10	212 x 91 x 66	737	38.2

Table 2 Characteristic compressive strength calculation for full size bricks

No.	Class interval	Frequency F_i	Deviation D_i	FiDi	$FiDi^2$	Cumulative frequency
1	18.5-20.5	2	0	0	0	2
2	20.5-22.5	2	1	2	2	4
3	22.5-24.5	2	2	4	8	6
4	24.5-26.5	0	3	0	0	6
5	26.5-28.5	1	4	4	16	7
6	28.5-30.5	0	5	0	0	7
7	30.5-32.5	1	6	6	36	8
8	32.5-34.5	0	7	0	0	8
9	34.5-36.5	1	8	8	64	9
10	36.5-38.5	1	9	9	81	10
$\sum=$		10		33	207	

$$x_o = \frac{\sum x_i}{n_i} = \frac{261.25}{10} = 26.125 N/mm^2$$

$$\bar{x} = x_o + w\left(\frac{\sum F_i D_i}{\sum F_i}\right) = 26.165 + 2\left(\frac{33}{10}\right) = 32.725 N/mm^2$$

$$\sigma = w\sqrt{\frac{\sum F_i D_i^2 - (\sum F_i D_i)^2 / \sum F_i}{\sum F_i - 1}} = 2\sqrt{\frac{207-(33)^2/10}{10-1}} = 6.603$$

Therefore, the characteristic compressive strength of the bricks is:

$$f_k = \bar{x} - 1.645\sigma = 32.725 - (1.645 \text{ x } 6.603) = 21.89 \text{ N/mm}^2$$

3.1.2 Small size clay bricks

As mentioned earlier, small size bricks are obtained by cutting a standard size brick into eight equal size pieces, which were used in the construction of half size prisms and eventually these bricks were planned to be used in the construction of half scale wall

3.1.3 Mortar designation

Mortar designation (iii) of BS5628: Part 1:1992 has been selected for the construction of the models. This type of mortar, which has a constituents proportion by volume of 1:1:5 (cement: lime: sand) is one of the most commonly used mortar in buildings construction in Malaysia and in most parts of the world.

For mortar testing purposes, twelve 75mm cubes have been prepared from the same mortar used in the construction of the models and cured hydraulically. Six cubes have been tested at the age of 7 days, which had an average compressive strength of 5.05N/mm^2 .The remaining six cubes have been tested after 28 days, which had an average compressive strength of 6.29N/mm^2.

3.1.4 Construction and Testing of the Models and their Results

3.1.4.1 Full scale prisms

Using full scale brick, 28 prisms in six sets have been constructed. Each set has one specific mortar joint thickness. The mortar joint thickness in different sets were 7.5mm, 10.0mm, 12.5mm, 15.0mm, 17.5mm and 20.0mm. After a period of 28 days, the prisms have been tested to obtain their axial compressive strength.

The vertical compressive strain in the prisms has been recorded using electrical resistance strain gauges installed on both larger vertical faces of the prisms as shown in Fig.1. The characteristic compressive strength for each set has been calculated using equation (1), (2),(3) and (4) which are shown in Table 3.

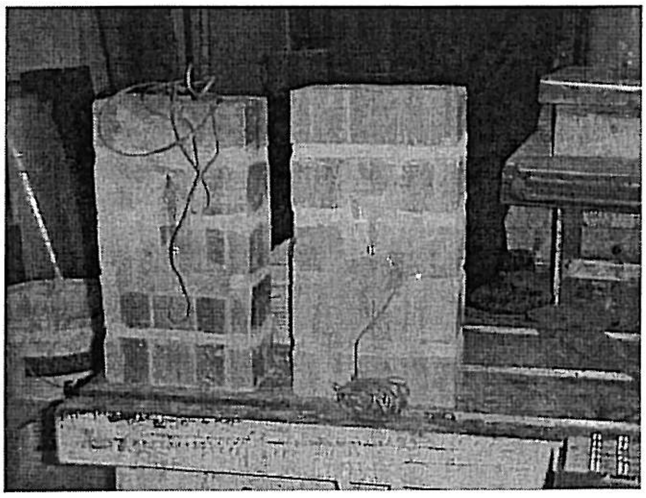


Fig. 1 Full scale prisms with electrical strain gauges installed on their larger vertical faces

Table 3 Characteristic compressive strength of full scale prisms

No.	Mortar joint thickness (mm)	Characteristic compressive strength (N/mm^2)
1	7.5	16.89
2	10.0	11.56
3	12.5	11.25
4	15.0	10.89
5	17.5	11.18
6	20.0	9.08

3.1.4.2 Half scale prisms

Using small scale bricks, a total of 35 prisms in six sets have been constructed. Again in order to establish an optimum mortar joint thickness for half scale wall panels (future planned research), six different mortar joint thickness have been adopted in the construction of the half scale prisms. The mortar joint thicknesses in the six sets were 3.75mm, 5.00mm, 6.00mm, 7.50mm, 8.75mm, and 10.00mm.

Similar instrumentation procedure to that of full size model has been used in these models as well. The prisms have been tested for their axial compressive strength after 28 days. The characteristic compressive strength of each set has been calculated using equation (1), (2), (3) and (4), which are shown in Table 4.

Table 4 Characteristic compressive strength of half scale models

No.	Mortar joint thickness (mm)	Characteristic compressive strength (N/mm^2)
1	3.75	19.19
2	5.00	16.39
3	6.00	13.70
4	7.50	13.39
5	8.75	12.72
6	10.0	12.09

3.1.5 Modulus of elasticity

For the determination of the modulus of elasticity of brick masonry, different researchers have proposed different values or formulas. The value of modulus of elasticity for the brickwork in the present study has been calculated using methods suggested by the various researchers[1],[5],[8],[11].

In the present study it has been proposed that an average value of modulus of elasticity of 5% of compressive strength and 33% of compressive strength of the brickwork may be adopted in the analysis and design of the structural brickwork. Since the stress-strain relationship for brickwork between 5% to 33% of its full compressive strength is almost linear, therefore the average value of modulus of elasticity will be acceptable.

The calculated average modulus of elasticity for full scale models and half scale models are shown in Table 5 and Table 6 respectively.

Table 5 Average modulus of elasticity for full scale models

No	Mortar joint thickness (mm)	Average modulus of elasticity (N/mm^2)
1	7.5	9300
2	10	7680
3	12.5	9130
4	15.0	6340
5	17.5	5960
6	20.0	2890

Table 6 Average modulus of elasticity for half scale models

No	Mortar joint thickness (mm)	Average modulus of elasticity (N/mm^2)
1	3.75	10370
2	5.00	7750
3	6.00	7610
4	7.50	7260
5	8.75	6060
6	10.0	4700

3.2 NUMERICAL ANALYSIS

Using eight-node isoparametric brick element, each full scale model has been discretized into 72 elements. The discretization is such that, bricks and mortar joints have been represented by separate layers of elements as shown in Figure 2.

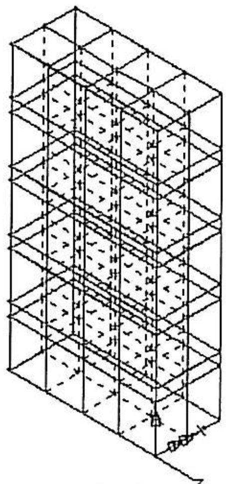


Figure 2: Prism discretized into 72 eight node brick elements

Each model is assumed to be subjected to axial compressive load as shown in Figure 3. The boundary condition adopted is that all nodes at the base of the models are assumed to be fixed. The models are assumed to be constructed from five local clay bricks having an average dimensions of 212 mm x 92 mm x 66mm (length x width x height), and each model with unique mortar joint thickness. There are six sets of models having different mortar joint thickness, which vary from 7.5 mm to 20.0 mm.

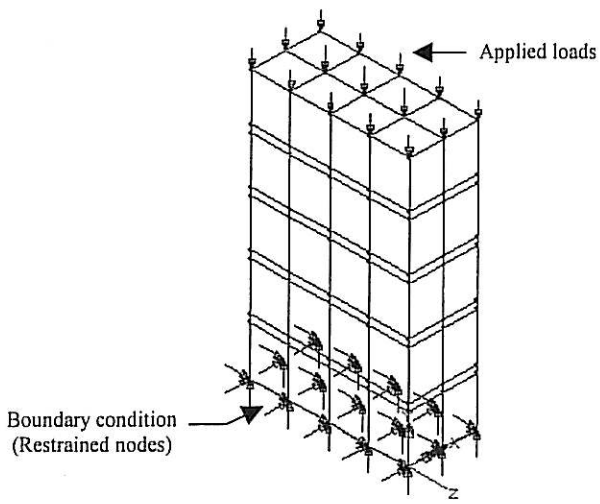


Figure 3: Typical model showing the applied load and boundary conditions

3.2.1 Idealization of models as a homogenized material

In this analysis the brickwork which is made from two different materials of clay bricks and mortar has been replaced by an equivalent homogenous material. This approach, which is used by many researchers in the field, assumes that brickwork is made from a single material [14]. However, a unique and equivalent material property for the brickwork has to be assigned. The equivalent material properties can be determined by experimental method, however, in the present study the material properties of the models have been calculated based on the recommendation of the Uniform Building Code (UBC-1991) of America [1].

UBC recommends that the modulus elasticity of masonry (E_m) in compression can be calculated using the following equation:

$$E_m = \frac{(1+\gamma_t)}{\left(1+\frac{\gamma_t}{\gamma_m}\right)} E_b \qquad \ldots(1)$$

where,

$$\gamma_t = \text{Thickness ratio} = \frac{t_j}{t_b}$$

$$\gamma_m = \text{Modulus ratio} = \frac{E_j}{E_b}$$

t_j = Thickness of mortar joints

t_b= Thickness of brick

E_j = Modulus of elasticity of joints i.e. mortar assumed to be 20000 N/mm^2

E_b = Modulus of elasticity of bricks assumed to be 37000 N/mm^2

Considering a model with a 7.5 mm mortar joint thickness, the modulus of elasticity of masonry can be calculated as follows:

$$\gamma_t = \frac{t_j}{t_b} = \frac{7.5}{66.0} = 0.114$$

$$\gamma_m = \frac{E_j}{E_b} = 0.541$$

$$\frac{\gamma_t}{\gamma_m} = \frac{0.114}{0.541} = 0.211$$

$$E_m = \left(\frac{1+0.114}{1+0.211}\right) 37000 = 34046.95 \text{ N/mm}^2$$

Using equation (1), the modulus of elasticity for various models has been calculated and shown in Table 7.

Table 7: Modulus of elasticity of prisms with different mortar joint thickness

No	Mortar joint thickness (mm)	Modulus of elasticity E_b(N/mm^2)	Poisson's Ratio
1	7.5	34046.95	0.25
2	10.0	33278.10	0.25
3	12.5	32721.08	0.25
4	15.0	31968.00	0.25
5	17.5	31405.34	0.25
6	20.0	30893.20	0.25

Poisson's ratio of 0.25 for brickwork as recommended by most of the researchers [10,14] has been adopted in the present study.

Using material properties from Table 7 and LUSAS computer software, three-dimensional finite element analyses of different models have been carried out. From the results, only the maximum vertical compressive stresses and maximum vertical compressive strains in the models have been tabulated and shown in Table 8.

Table 8: Finite element results for models idealized as a homogenized material

Mortar joint thickness (mm)	Maximum vertical compressive stress (N/mm^2)	Maximum vertical compressive strain (mm/mm)
7.5	7.89	0.00415
10.0	7.55	0.00405
12.5	7.30	0.00400
15.0	6.42	0.00370
20.0	6.23	0.00320

3.2.2 Idealization of models as a composite material

In this analysis the model are assumed to be made from two different materials namely clay bricks and mortar [11,14]. The modulus of elasticity of clay brick is assumed to be $E_b = 37000$ N/mm^2 with a Poisson's ratio of $\nu_b = 0.1$. The modulus of elasticity of mortar is assumed to be $E_j = 20000$ N/mm^2 and $\nu_j = 0.25$. The mortar is assumed to be having a mix proportion of 1:1:5 (cement : sand : lime). It is also assumed that the brick and mortar are perfectly bonded together. The finite element discretization of the models are carried out in such a manner that mortar joints and bricks are represented by separate layers of elements. The non-linearity considered in the analysis of the models is only material nonlinearity. This is because, mortar having lower compressive strength behave as a non-linear material. The 3-D finite element analyses of the models have been carried out and only maximum vertical compressive stresses and maximum vertical compressive strains in the models are represented in Table 9.

Table 9: Finite element results for models idealized as a composite material

Mortar joint thickness (mm)	Maximum vertical compressive stress (N/mm^2)	Maximum vertical compressive strain (mm/mm)
7.5	7.58	0.00413
10.0	7.25	0.00402
12.5	7.13	0.00340
15.0	6.72	0.00330
20.0	6.21	0.00315

CHAPTER IV

COMPARISON AND DISCUSSION OF RESULTS

4. 1 Experimental results

The knowledge of stress-strain relationship for brickwork in compression is frequently required in the structural design of load bearing building structures. Therefore present investigation has been carried out to establish the nature of the stress-strain curve and to asses an average value of young's modulus for brickwork constructed from local materials.

In most of the codes of practice the prism test is adopted as the basis for the assessment of the design strength of masonry in compression [9],[10]. In the present study a total number of 63 prisms including both full scale and half scale have been constructed and tested to evaluate their compressive strength.

Generally, the results indicate that in both cases when the thickness of the mortar joint in prisms increases the compressive strength of masonry decreases. The maximum compressive strength in the case of full scale models is obtained when the mortar joint thickness is 7.5mm. The effect of mortar joint thickness on compressive strength for full scale prisms are shown in Fig. 4. Similarly, in the case of half scale models the maximum compressive strength is achieved when the mortar joint thickness is 3.75mm.

A comparison of the compressive strength given in Table 2(a) of BS 5628: Part 1 with the result obtained from present investigation shows that the strength of the models are higher by 88% than those recommended by the code for the same type of units, mortar joint thickness and mortar designation.

The general mode of failure in almost all models was compression failure, by developing tension cracks parallel to the axis of loading.

The results obtained indicates the stress-strain relationship is approximately parabolic. However under service conditions brickwork is stressed only up to a fraction of its ultimate load, therefore in normal conditions, the assumption of a linear stress-strain curve is acceptable as adopted by most of the researchers in this field.

Based on the above mentioned assumptions, brick masonry can be treated as a linear elastic material.

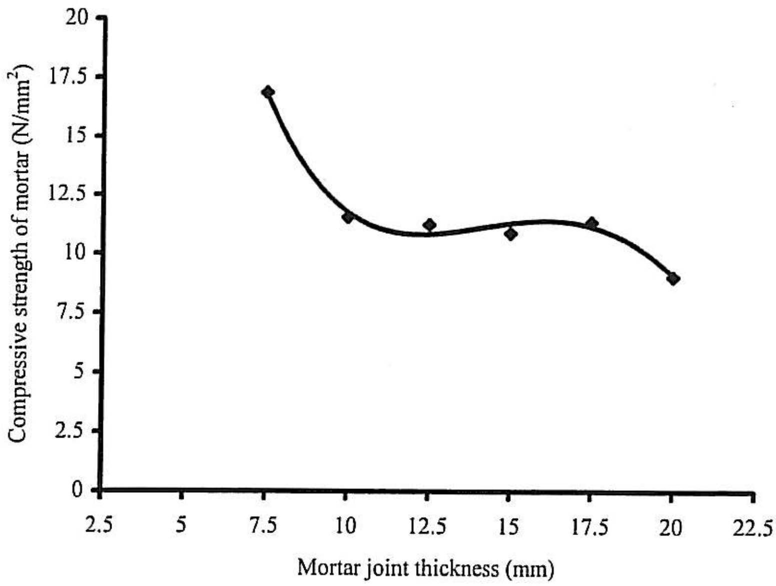


Fig. 4 Effect of mortar joint thickness on masonry compressive strength in full scale models.

4.2 Results of numerical analysis

Assuming as linear elastic materials, finite element analyses of models under axial loads is carried out. In the actual case, the compressive stress in the masonry will be a friction of its ultimate strength, therefore, again the assumption of linear elastic stress strain relationship in the clay brick masonry can be adopted for the design purposes. The assumption is also valid since the assumed partial safety factor of the prisms will be very high. Fig. 5 shows deformed shape of the model under action of compressive load.

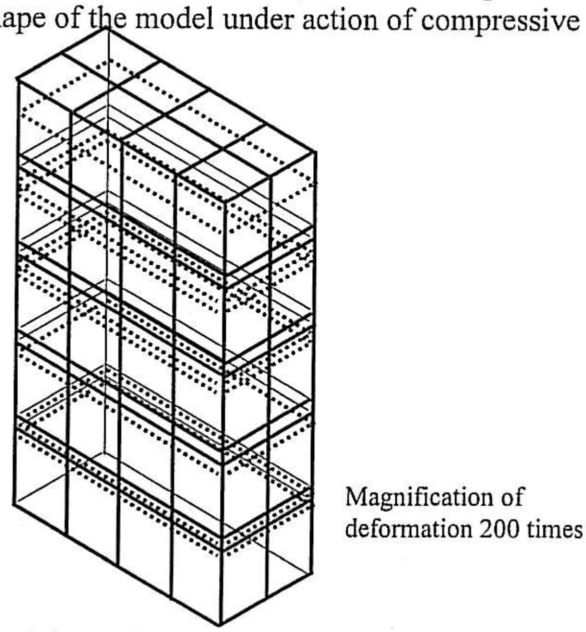
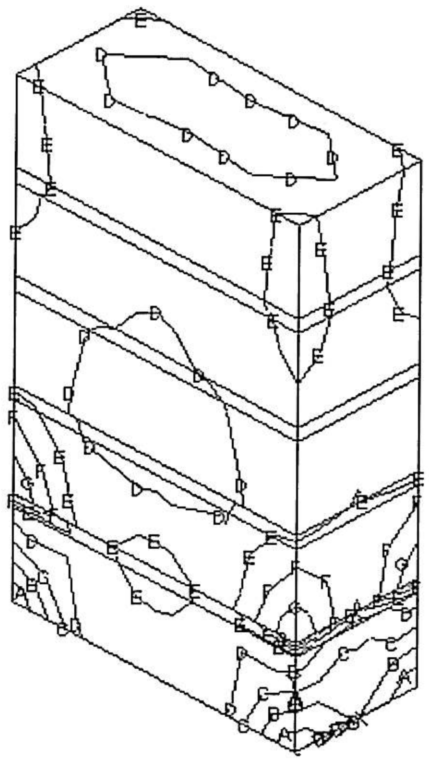


Fig. 5. Deformed shape of the model with 10mm mortar joint thickness

Fig.6 below represents the contours for vertical stress from the finite element study of full scale prism having 10mm mortar joint thickness.



Contours of vertical stress σ_y

Legend

A -7.5 N/mm^2
B -7.4 N/mm^2
C -7.3 N/mm^2
D -7.2 N/mm^2
E -7.1 N/mm^2
F -7.0 N/mm^2
G -6.9 N/mm^2

Fig.6.Vertical stress contour in the model with 10mm mortar joint thickness

The comparison of stress-strain curves for both cases of the FEM analyses and the experimental study are shown in Fig.7 to Fig.12. The stress strain curve obtained from both analyses shows that the maximum compressive strength is higher for homogenized material than the idealization as a composite material. Homogenized model acts as assignation of one material, so dispersion of load can be at 45^0. However in composite, which is an arrangement of two layered materials, the same dispersion can't be expected. The mortar joint having lower strength will cause reduction in the masonry strength. Actual compressive strength of the masonry determined by experimental method is much higher than the strength obtained by numerical method. However the idealization as a composite material will be adopted since brick masonry is actually layered material.

The comparison of experimental and finite element results indicates that the compressive strength of masonry obtained by experimental method is about 50% higher than those obtained by finite element method. Therefore, to get the actual compressive design strength of the brick masonry, the finite element analysis results should be enhanced by a magnification factor of 1.5.

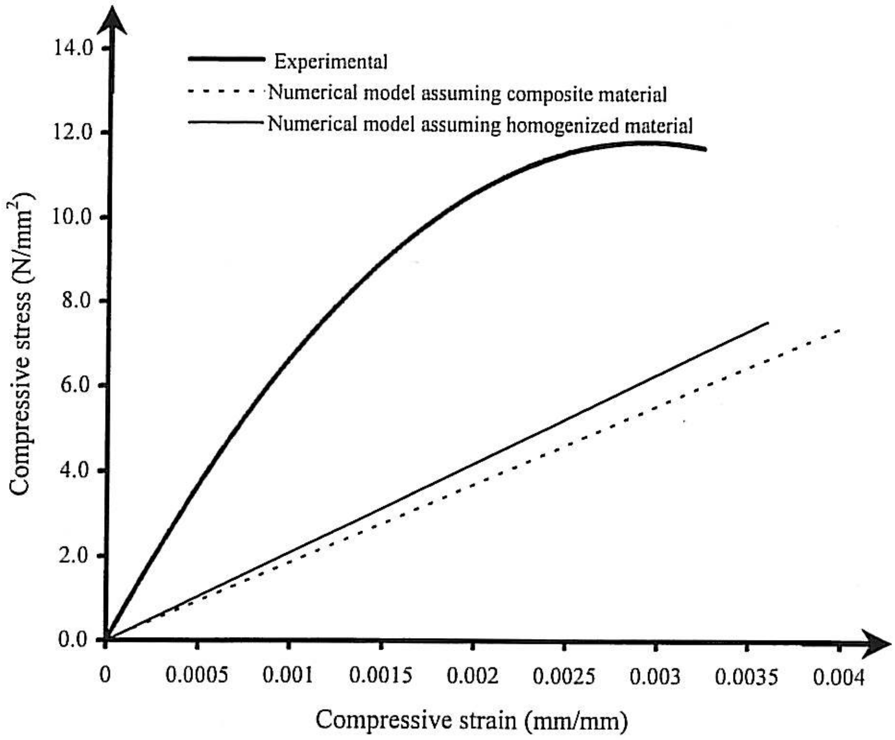


Fig. 7. Stress strain curve for model with 7.5mm mortar joint thickness

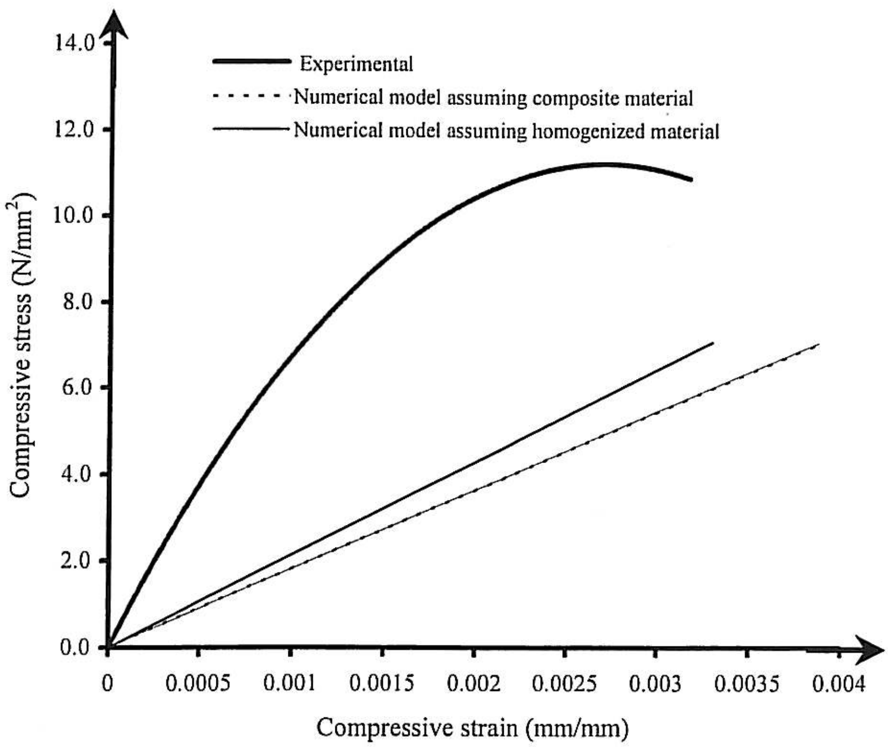


Fig. 8. Stress strain curve for model with 10.0mm mortar joint thickness

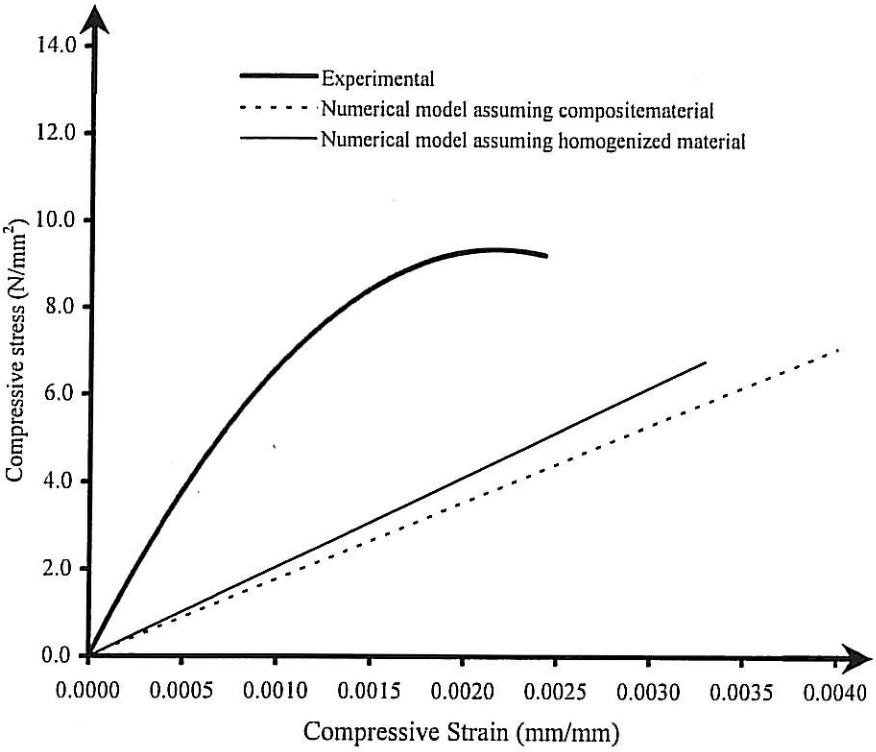


Fig. 9. Stress strain curve for model with 12.5mm mortar joint thickness

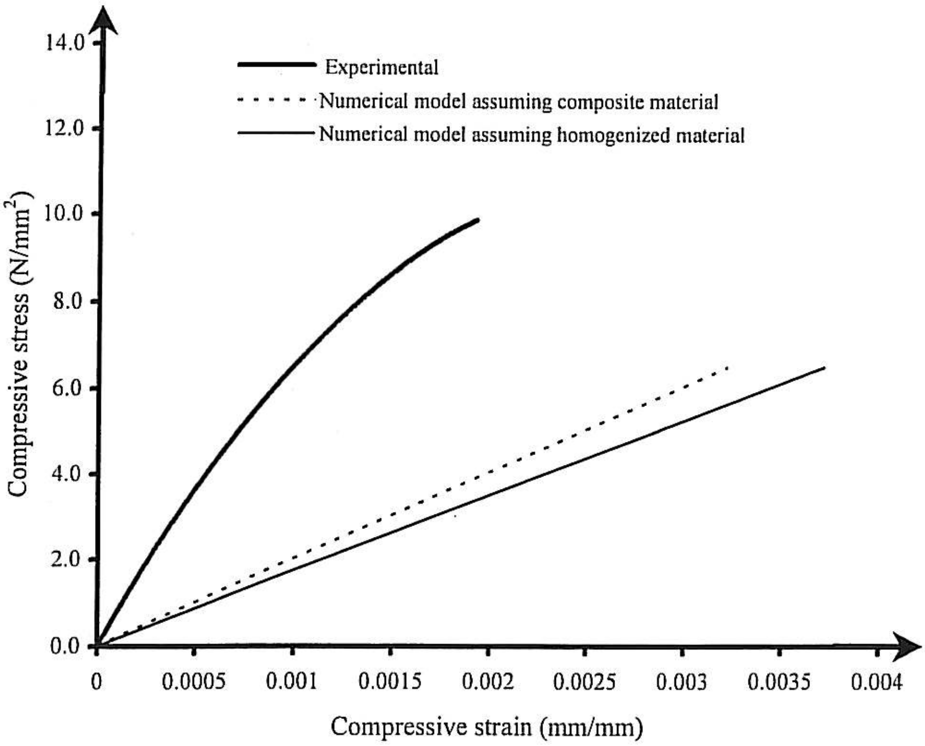


Fig. 10. Stress strain curve for model with 15.0mm mortar joint thickness

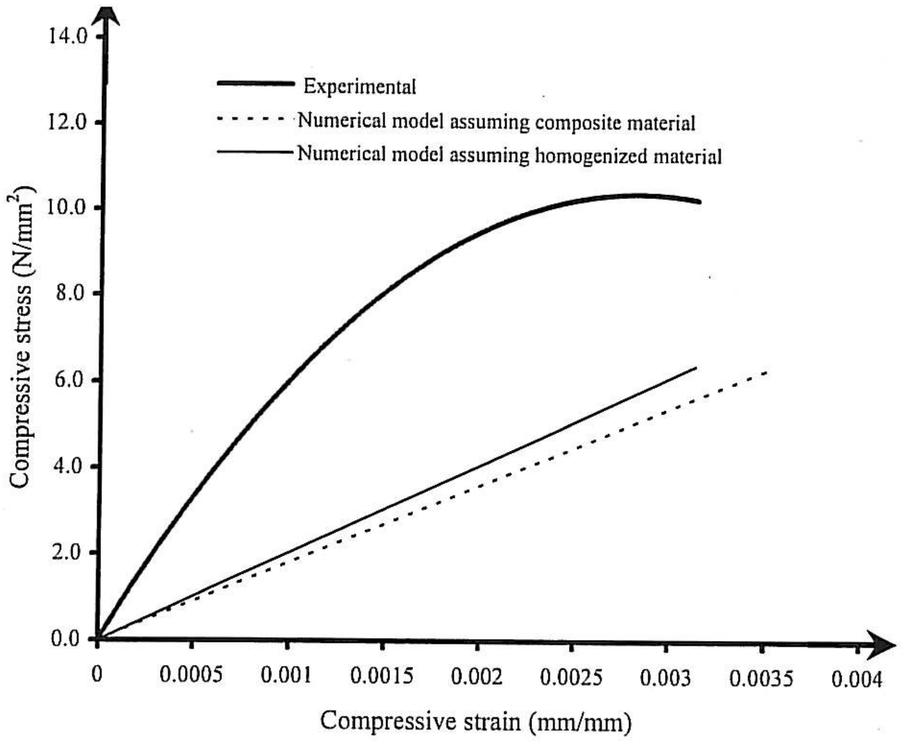


Fig. 11. Stress strain curve for model with 17.5mm mortar joint thickness

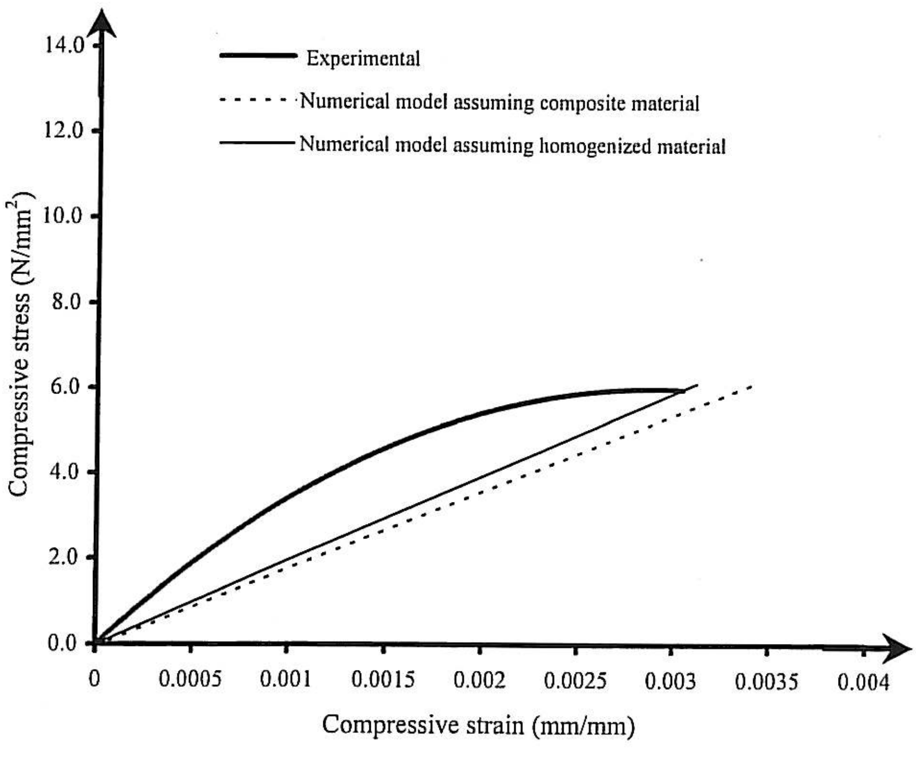


Fig. 12. Stress strain curve for model with 20.0mm mortar joint thickness

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

1. Mode of failure: Almost all models loaded in uniform compression failed by the development of tension cracks parallel to the axis of loading.

2. The compressive characteristic strength of the models (i.e. masonry) was smaller than the characteristic compressive strength of the bricks used in the models. On other hand, the compressive strength of the models was much higher than the average compressive strength of the mortar cubes.

3. A comparison of the compressive strength given in Table 2(a) of BS 5628: Part 1 with the results obtained from present study shows that the models exhibits much higher strength than the values recommended by BS Code. Hence, higher factor of safety than that recommended by BS Code.

4. Generally, it has been observed that by increasing the mortar joint thickness the strength of the masonry will decrease. The maximum compressive strength in the case of full scale models is obtained when the thickness of the mortar joint is 7.5mm. Similarly, in the case of half scale models, the maximum compressive strength is obtained when the thickness of the mortar joint is 3.75mm.

5. There is a vast difference in the values of modulus of elasticity of the brickwork calculated using formulas suggested by various researchers. Therefore, it is recommended that a modulus of elasticity of an average value of the 5% of the compressive strength and 33% of the compressive strength of the brickwork under axial compression may be adopted for the analysis and design purposes.

6. In actual conditions, the structural brick masonry will be loaded up to friction of its ultimate strength. Therefore the assumption of linear elastic stress strain relationship can easily be adopted.

7. It is recommended that idealization, as a composite material should be made for numerical analysis. This is because brick masonry is actually an arrangements of layered materials.

8. For the deign purposes, the compressive strength of brick masonry obtained from finite element analysis should be magnified with a minimum factor of 1.5 in order to get the actual strength of the structural brickwork.

Acknowledgement

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LOAD BEARING BRICKWORK METHOD IN BUILDING INDUSTRIES

By

Prof. Madya Dr. Jahangir Bakhteri

Faculty of Civil Engineering

Universiti Teknologi Malaysia

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LOAD BEARING BRICKWORK METHOD IN BUILDING INDUSTRIES

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1. INTRODUCTION

Brick masonry is probably the oldest building material that still finds wide use in today's building industries. It is well known that brickwork forms an attractive cladding and it is durable material with good thermal and acoustic and excellent fire resistance. What is not so well known is that it is an economic structural material that can often be used to build faster, and more cheaply and easily than its rivals of steel and concrete. Therefore, the usage of normal plain brick masonry in building constructions is an economic, fast and simple technique for producing durable, and attractive structures. Load bearing construction is still the preferred method for housing throughout Europe, America, Australia, New Zealand, China and in most part of Asia and about 70% of the world population live in load bearing houses. However, this method of construction has yet to be effectively applied in Malaysia.

2. DESIGN CONSIDERATION IN LOAD BEARING BRICKWORK

Load bearing brickwork (LBB) method is most appropriately used for buildings in which the floor areas are subdivided into a relatively large number of rooms of small to medium size and in which the floor plan is repeated on each storey throughout the height of the building. These considerations give ample opportunity for disposing load bearing walls, continuous from foundation to roof level, and because of the moderate floor spans, not called upon to carry unduly heavy concentrations of vertical loads. The types of buildings which are compatible with these requirements include flats, hostels, hotels and other residential buildings. Stair walls, lift shafts, and service ducts play an important part in deciding layout and are often of primary importance in providing lateral rigidity. From the structural design point of view the load bearing brickwork walls have to support all the superstructure loads such as roof, walls, and floor slabs and the lateral loads such as wind and soil pressures.The LBB method differs from the conventional RCC method where beams and Columns support the loads while in LBB the walls act as structural elements which provide support and stability for the building.

3. CONSTRUCTION MATERIALS

(a) BRICKS

LBB can be constructed using clay bricks and cement sand blocks. BS 5628: Part-1:1992 specifies the minimum strength of 5 N/mm2 and 2.8 N/mm2 for bricks and blocks respectively, for use in unreinforced masonry. The recommended standard size of brick is 215 x 105.2 x 65mm with maximum tolerance of 7mm.

(b) MORTAR

Mortar is the second component in brickwork which for load bearing brickwork should be cement : lime : sand mix. The proportion varies on the basis of strength requirement. The thickness of the mortar joint is normally about 10 ~ 12 mm. Lime is added to cement mortar to improve the workability, water retention, and bonding properties. Depending on condition and requirement, cement-sand mortar and cement-sand-plasticizer mortar are also specified by BS 5628: Part-3.

4. FOUNDATION

The load from structural masonry form tends to be more uniformly distributed and therefore, at foundation level, there is less need to spread the load to reduce the bearing pressure. This makes for economies where, strip, pad or raft foundations are employed.A very unfavourable soil condition may necessitate piling with ground beams.

5. BOND

Local bricklayers in Malaysia are experienced enough to work on load bearing brickwork since the work is quite similar to that of laying facing bricks and some initial supervision of the bricklaying work is required.This is needed to ensure that all the bonds, bricklaying and joints are done in accordance with the provided structural details of load bearing brickworks. Fig. 1 shows some of these brickwork bonds and details.

6. ADVANTAGES OF THE LOAD BEARING BRICKWORK

(a) Safety

Incorporating all the safety factors recommended by the BS: 5628 Part 1, 2 & 3, the factor of safety in load bearing brickwork will be between 4 & 6.

(b) Economy

The cost saving from the usage of load bearing brickwork system will range from 10% to 20% of the total cost of the building.

(c) Construction Time

Compared to the conventional method, the LBB will save 10% to 30% of the construction time.

(d) Appearance & Durability

Brick masonry is well proven building material possessing excellent properties in terms of appearance, durability, good thermal and acoustic insulation, and better fire resistance.

8. RESEARCH

Presently an extensive research program on LBB is undertaken in the Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai, and in the initial stage of which the investigation on "Load Carrying Capacity and Failure Mode in Flanged Brick Wall Panels With Door Opening" is going on.

9. CONCLUSIONS

Considering the above mentioned advantages of the load bearing brickwork in building construction, it can be said that, it is a suitable replacement for the steel and concrete in low cost and medium low cost housing, and low-rise hotels and office apartments.The cost saving is achieved by minimizing the use of reinforced concrete, more economical foundation designs due to the relatively uniform loadings. Using flat slab floor system will eliminate the beams' formwork. In this system a quick start-up of wall constructionand as well as continuous construction due to the rapid strength gained from the brickwork is an additional advantage.

Finally it can be concluded that the load bearing brickwork construction method is a cost effective and time effective method because, materials are cheap, easily and widely available and the construction technique familiar to the local labourers. In the case where facing bricks are used, it eliminates fungusgrowth, peeling paint and enhance aestheticism mean while reduces maintenance cost.

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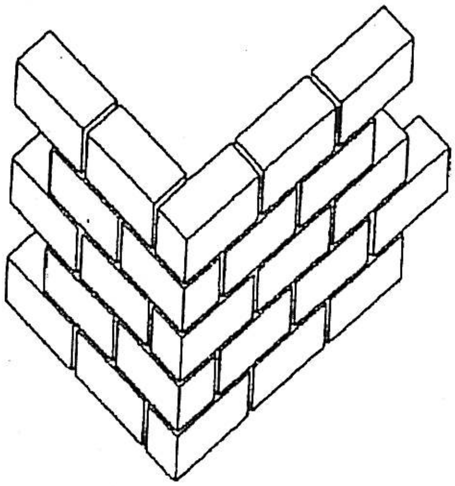
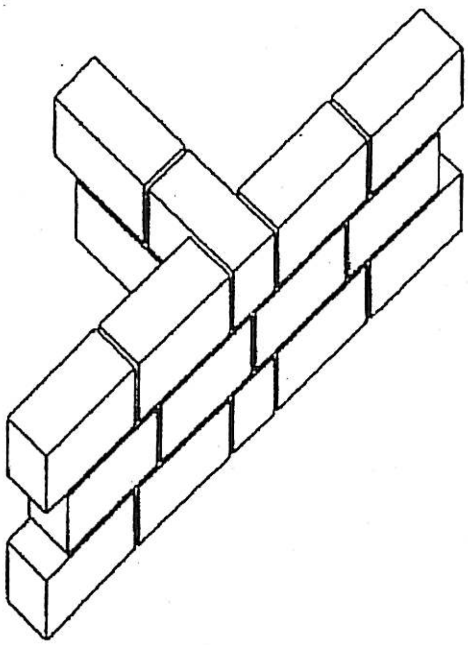
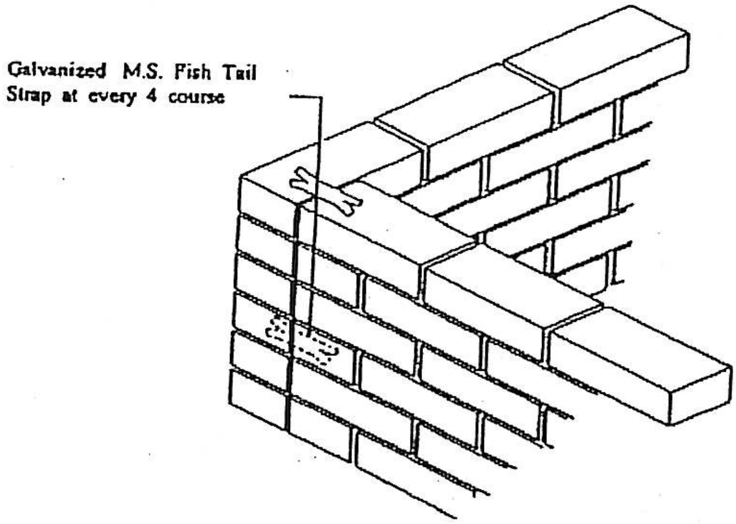


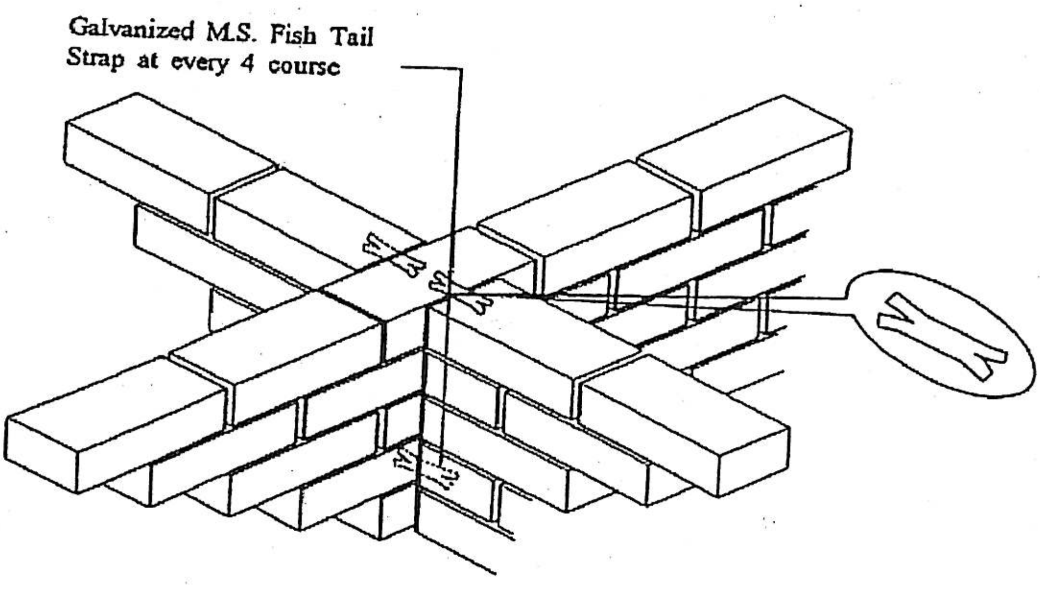
CORNER BOND



BOND TO INTERNAL WALL

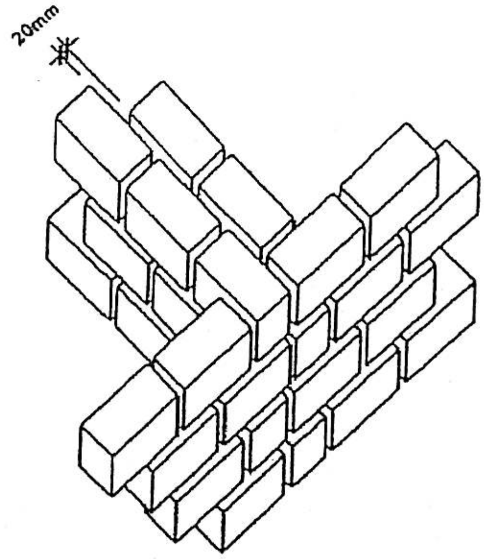


JOINT AT CROSS-WALLS USING FISH TAIL TIES

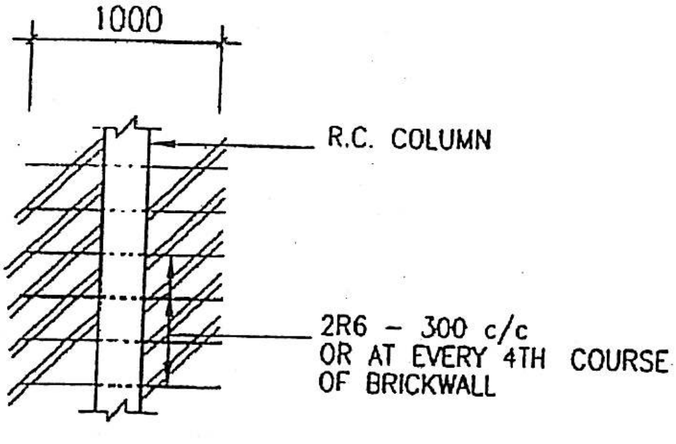


INTERNAL CROSS-WALLS TIED

TOGETHER BY METAL TIES



TYPYCAL MOVEMENT JOINT DETAIL



RC COLUMN AND WALL JOINT DETAIL

Proceedings of the 5th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2003)
26 – 28 August 2003 Johor Bahru, MALAYSIA

MECHANICAL BEHAVIOUR OF STRUCTURAL BRICK MASONRY: AN EXPERIMENTAL EVALUATION

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Abstract. *The aim of this investigation is to study the mechanical behavior of structural clay brick masonry made from local materials and to investigate the effects of mortar joint thickness on the brickwork strength. Various sets of prisms, both full scale and half scale made from five bricks, and having different mortar joint thickness have been tested. Using a simple statistical method, the characteristic compressive strength of the structural brickwork under compression for each set has been calculated. An attempt has also been made to assess the modulus of elasticity of the brick masonry. In conclusion the effect of the mortar joint thickness on compressive strength of the masonry has been reported, and an approximate modulus of elasticity of the brickworks for analysis and design has been proposed.*

1. Introduction

Brick masonry has been used as a load bearing material for centuries. In early gravity structures, level of stress was low and factor of safety against compression failure was high, so that detailed knowledge of compressive behavior was not essential. However, in recent years, the usage of thin walls that provide optimum space in buildings has caused the wall to be highly stressed under vertical loads. The needs for better knowledge of the behavior of vertically loaded walls has led to substantial research in this field.

The purpose of this investigation is to study the mechanical behavior of structural brickwork with particular reference to Malaysian condition. In the initial part of the study, investigation has been carried out to study the effects of mortar joint thickness on the compressive strength of masonry. In the second part of the study, an attempt has been made to determine the approximate modulus of elasticity for the tested models.

The models include both full size prisms and half size prisms. In the case of full size prisms, the models are constructed using five standard size bricks (215mm length x 102.5mm width x 65mm height)[3],[4]. For the construction of half scale prisms, a standard size brick has been cut into eight equal size pieces each one having a dimension of 107.5mm x 51.25mm x 32.5mm and the models have been constructed using five bricks.

2. Selection and Testing of Materials for the Models

2.1 Clay bricks

2.1.1 Full size bricks

Ten full size clay bricks were selected randomly from the same batch of bricks which were used in the construction of the prisms. These bricks were tested to determine their compressive strength under axial compressive load. Table 1 shows the maximum compressive strength of the bricks.

The variability in strength of bricks for any particular batch is quite considerable. This makes it important to use a statistical method in evaluating their mean strength[5],[11]. The characteristic compressive strength of the tested bricks has been calculated using the following formula and generated data in Table 2

$$f_k = \bar{x} - 1.64\sigma \tag{1}$$

$$x_o = \frac{\sum x_i}{n_i} \tag{2}$$

$$\bar{x} = x_o + w\left(\frac{\sum F_i D_i}{\sum F_i}\right) \tag{3}$$

$$\sigma = w\sqrt{\frac{\sum F_i D_i^2 - (\sum F_i D_i)^2 / \sum F_i}{\sum F_i - 1}} \tag{4}$$

where, x_o = average compressive strength of specimens

$\bar{x}$ = mean

w = width of the class interval, selected as 2.0 N/mm^2

n = number of models tested

σ = standard deviation

F_i = number of observations falling in the i^{th} class interval

D_i = deviation

Table 1 Compressive strength of tested clay bricks

No.	Brick size l x w x h (mm)	Maximum load (kN)	Compressive strength (N/mm^2)
1	206 x 90 x 66	505	27.24
2	214 x 91 x 67	360	18.49
3	212 x 91 x 66	379	19.65
4	206 x 91 x 67	428	22.83
5	217 x 94 x 66	452	22.16
6	217 x 94 x 66	473	23.19
7	209.5 x 89 x 67	605	32.45
8	214 x 93 x 66	423	21.25
9	204 x 87 x 66	639	35.74
10	212 x 91 x 66	737	38.20

Table 2 Characteristic compressive strength calculation for full size bricks

No.	Class interval	Frequency Fi	Deviation Di	FiDi	$FiDi^2$	Cumulative frequency
1	18.5- 20.5	2	0	0	0	2
2	20.5- 22.5	2	1	2	2	4
3	22.5- 24.5	2	2	4	8	6
4	24.5- 26.5	0	3	0	0	6
5	26.5- 28.5	1	4	4	16	7
6	28.5- 30.5	0	5	0	0	7
7	30.5- 32.5	1	6	6	36	8
8	32.5- 34.5	0	7	0	0	8
9	34.5- 36.5	1	8	8	64	9
10	36.5- 38.5	1	9	9	81	10
$\sum =$		10		33	207	

$$x_o = \frac{\sum x_i}{n_i} = \frac{261.25}{10} = 26.125 N / mm^2$$

$$\bar{x} = x_o + w\left(\frac{\sum F_i D_i}{\sum F_i}\right) = 26.165 + 2\left(\frac{33}{10}\right) = 32.725 N / mm^2$$

$$\sigma = w\sqrt{\frac{\sum F_i D_i^2 - (\sum F_i D_i)^2 / \sum F_i}{\sum F_i - 1}} = 2\sqrt{\frac{207 - (33)^2 / 10}{10 - 1}} = 6.603$$

Therefore, the characteristic compressive strength of the bricks is:

$$f_k = \bar{x} - 1.645\sigma = 32.725 - (1.645 \text{ x } 6.603) = 21.89 \text{ N/mm}^2$$

2.1.2 Small size bricks

As mentioned earlier, small size bricks are obtained by cutting a standard size brick into eight equal size pieces, which were used in the construction of half size prisms and eventually these bricks will be used in the construction of half scale wall panels in a future planned research. Ten bricks were selected randomly and tested for their compressive strength. Equation (1),(2),(3) and (4) were used to calculate the characteristic compressive strength of the bricks. The bricks had a characteristic compressive strength of $56.62N / mm^2$.

2.2 Mortar

Mortar designation (iii) of BS5628: Part 1:1992 has been selected for the construction of models. This type of mortar, which has a constituents proportion by volume of 1:1:5 (cement: lime: sand) is one of the most commonly used mortar in buildings construction in Malaysia and in most parts of the world.

For mortar testing purposes, twelve 75mm cubes have been prepared from the same mortar used in the construction of the models and cured hydraulically. Six cubes have been tested at the age of 7 days, which have an average compressive strength of 5.05N/mm^2 .The remaining six cubes have been tested after 28 days, which have an average compressive strength of 6.29N/mm^2.

3. Construction and Testing of the Models and their Results

3.1 Full scale prisms

Using full scale brick, 28 prisms in six sets have been constructed. Each set has one specific mortar joint thickness. The mortar joint thickness in different sets were 7.5mm, 10.0mm, 12.5mm, 15.0mm, 17.5mm and 20.0mm. After a period of 28 days, the prisms have been tested to obtain their axial compressive strength.

The vertical compressive strain in the prisms has been recorded using electrical resistance strain gauges installed on both larger vertical faces of the prisms as shown in Fig.1. The characteristic compressive strength for each set has been calculated using equation (1), (2),(3) and (4) which are shown in Table 3. The average stress-strain curve for each set is drawn in Fig. 2.

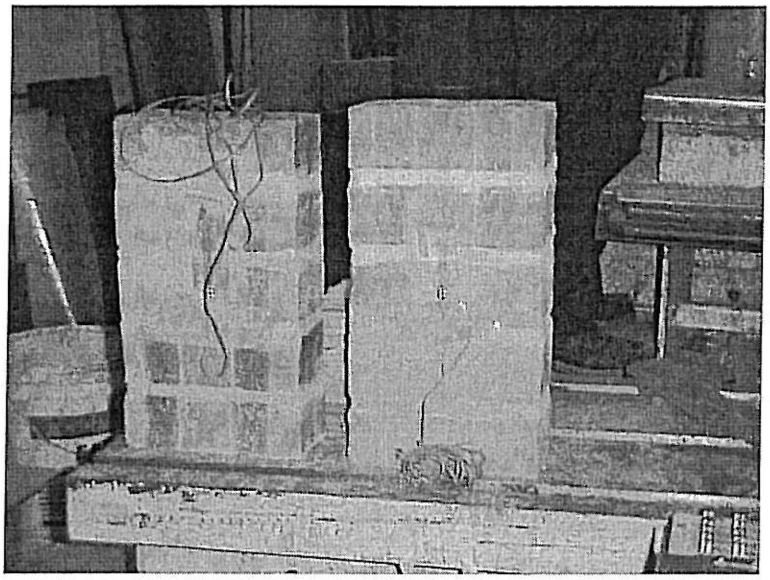

Fig. 1 Full scale prisms with electrical strain gauges installed on their larger vertical faces

Table 3 Characteristic compressive strength of full scale prisms

No.	Mortar joint thickness (mm)	Characteristic compressive strength (N/mm^2)
1	7.5	16.89
2	10.0	11.56
3	12.5	11.25
4	15.0	10.89
5	17.5	11.18
6	20.0	9.08

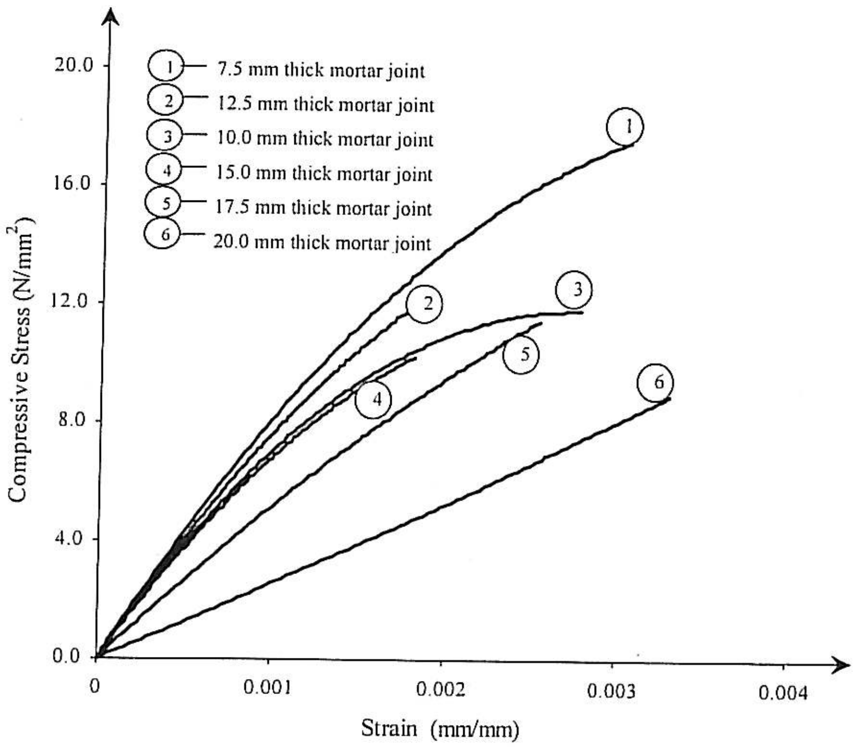

Fig. 2 Stress-strain curves for full scale models

3.2 Half scale prisms

Using small scale bricks, a total of 35 prisms in six sets have been constructed. Again in order to establish an optimum mortar joint thickness for half scale wall panels (future planned research), six different mortar joint thickness have been adopted in the construction of the half scale prisms. The mortar joint thicknesses in the six sets were 3.75mm, 5.00mm, 6.00mm, 7.50mm, 8.75mm, and 10.00mm.

Similar instrumentation procedure to that of full size model has been used in these models as well. The prisms have been tested for their axial compressive strength after 28 days. The characteristic compressive strength of each set has been calculated using equation (1), (2), (3) and (4), which are shown in Table 4. The average stress-strain curve for each set is drawn in Fig. 3.

Table 4 Characteristic compressive strength of half scale models

No.	Mortar joint thickness (mm)	Characteristic compressive strength (N/mm^2)
1	3.75	19.19
2	5.00	16.39
3	6.00	13.70
4	7.50	13.39
5	8.75	12.72
6	10.0	12.09

3.3 Modulus of elasticity

For the determination of the modulus of elasticity of brick masonry, different researchers have proposed different values or formulas. The value of modulus of elasticity for the brickwork in the present study has been calculated using methods suggested by the various researchers. The values varies from 16700N/mm^2 to 3950 N/mm^2 [1],[5],[8],[11].

In the present study it has been proposed that an average value of modulus of elasticity of 5% of compressive strength and 33% of compressive strength of the brickwork may be adopted in the analysis and design of the structural brickwork. Since the stress-strain relationship for brickwork between 5% to 33% of its full compressive strength is almost linear, therefore the average value of modulus of elasticity will be acceptable.

The calculated average modulus of elasticity for full scale models and half scale models are shown in Table 5 and Table 6 respectively.

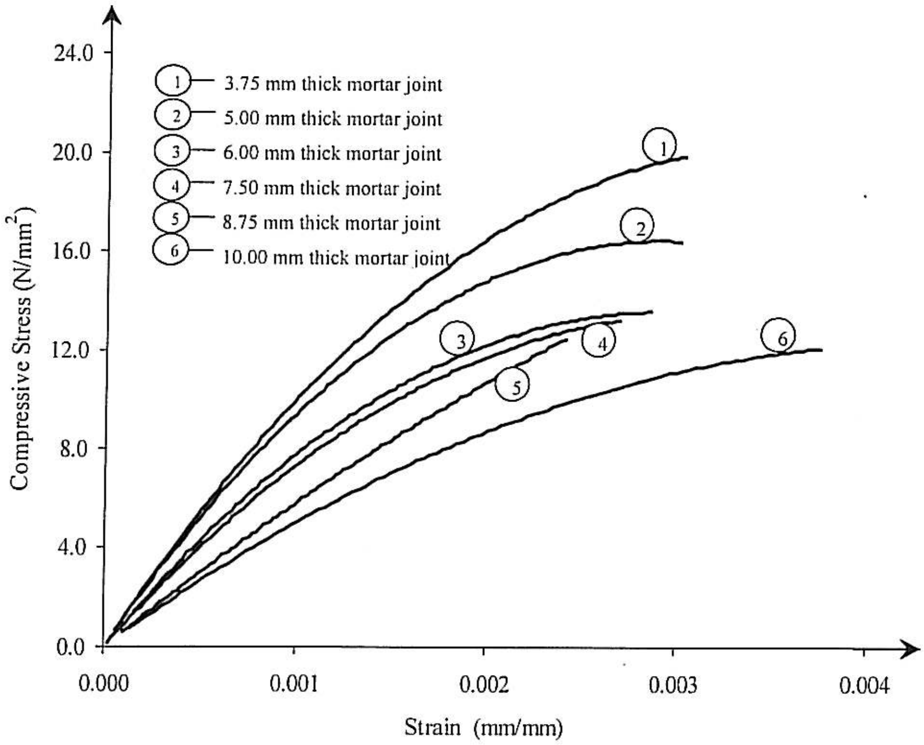

Fig. 3 Strain-stress curves for half scale models

Table 5 Average modulus of elasticity for full scale models

No	Mortar joint thickness (mm)	Average modulus of elasticity (N/mm^2)
1	7.5	9300
2	10	7680
3	12.5	9130
4	15.0	6340
5	17.5	5960
6	20.0	2890

Table 6 Average modulus of elasticity for half scale models

No	Mortar joint thickness (mm)	Average modulus of elasticity (N/mm^2)
1	3.75	10370
2	5.00	7750
3	6.00	7610
4	7.50	7260
5	8.75	6060
6	10.0	4700

4. Discussion of Results

The knowledge of stress-strain relationship for brickwork in compression is frequently required in the structural design of load bearing building structures. Therefore present investigation has been carried out to establish the nature of the stress-strain curve and to assess an average value of Young's modulus for brickwork constructed from local materials.

In most of the codes of practice the prism test is adopted as the basis for the assessment of the design strength of masonry in compression [9],[10]. In the present study a total number of 63 prisms including both full scale and half scale have been constructed and tested to evaluate their compressive strength.

Generally, the results indicate that in both cases when the thickness of the mortar joint in prisms increases the compressive strength of masonry decreases. The maximum compressive strength in the case of full scale models is obtained when the mortar joint thickness is 7.5mm. The effect of mortar joint thickness on compressive strength for full scale prisms are shown in Fig. 4. Similarly, in the case of half scale models the maximum compressive strength is achieved when the mortar joint thickness is 3.75mm.

A comparison of the compressive strength given in Table 2(a) of BS 5628: Part 1 with the result obtained from present investigation shows that the strength of the models are higher by 88% than those recommended by the code for the same type of units, mortar joint thickness and mortar designation.

The general mode of failure in almost all models was compression failure, by developing tension cracks parallel to the axis of loading as shown in Fig. 5.

The results obtained indicate the stress-strain relationship is approximately parabolic. However under service conditions brickwork is stressed only up to a fraction of its ultimate load, therefore in normal conditions, the assumption of a linear stress-strain curve is acceptable as adopted by most of the researchers in this field.

Based on the above mentioned assumptions, brick masonry can be treated as a linear elastic material.

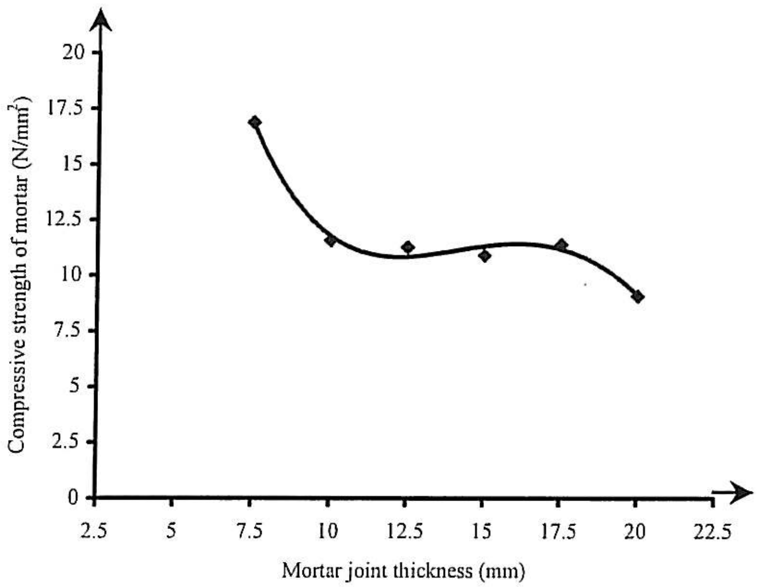

Fig. 4 Effect of mortar joint thickness on masonry compressive strength in full scale models.

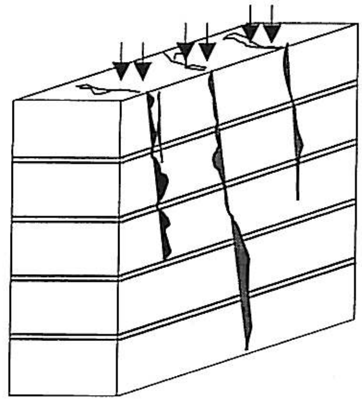

Fig. 5 Typical failure pattern in the prisms under axial compressive load

5. Conclusions

1. Mode of failure: Almost all models loaded in uniform compression failed by the development of tension cracks parallel to the axis of loading.
2. The compressive characteristic strength of the models (i.e. masonry) was smaller than the characteristic compressive strength of the bricks used in the models. On the other hand, the compressive strength of the models was much higher than the average compressive strength of the mortar cubes.
3. A comparison of the compressive strength given in Table 2(a) of BS 5628: Part 1 with the results obtained from the present study shows that the models exhibit much higher strength than the values recommended by BS Code. Hence, higher factor of safety than that recommended by BS Code.
4. Generally, it has been observed that by increasing the mortar joint thickness the strength of the masonry will decrease. The maximum compressive strength in the case of full scale models is obtained when the thickness of the mortar joint is 7.5mm. Similarly, in the case of half scale models, the maximum compressive strength is obtained when the thickness of the mortar joint is 3.75mm.
5. There is a vast difference in the values of modulus of elasticity of the brickwork calculated using formulas suggested by various researchers. Therefore, it is recommended that a modulus of elasticity of an average value of the 5% of the compressive strength and the 33% of compressive

strength of the brickwork under axial compression may be adopted for the analysis and design purposes.

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FINITE ELEMENT MODELLING OF STRUCTURAL CLAY BRICK MASONRY SUBJECTED TO AXIAL COMPRESSION

Jahangir Bakhteri[1], Ahmad Mahir Makhtar[2] & Shamala Sambasivam[3]

Abstract: This paper presents the numerical verifications of the experimental investigation on the effect of mortar joint thickness on compressive strength characteristics of axially loaded brick-mortar prisms. The three dimensional micro modeling of the prisms was based on two approaches: firstly, models were assumed to be made of homogeneous material; the second approach envisages the models as composite material made of brick and mortar. The later modeling approach, which assumed the prism to be made of composite material, gave more accurate prediction of the stress distribution in the prisms and also the failure loads predictions were in good agreement with the experimental results, suggesting that this modeling approach with composite material assumption is more appropriate than the homogenous material assumption. In the present work a strength magnification factor has also been proposed for the design purposes, which can be used to assess the experimental compressive strength of the brick masonry from its finite element analysis results.

Keywords: Masonry, homogenization, composite, stress, strain

Abstrak: Kertas kerja ini membentangkan pembuktian berangka hasil dari ujikaji kesan ketebalan sambungan lepa ke atas sifat kekuatan mampatan bagi prisma bata-lepa yang berbeban paksi. Pemodelan mikro tiga dimensi bagi prisma-prisma tersebut dibuat dengan dua kaedah: yang pertama, dianggap model-model tersebut telah dibina dengan bahan sejenis; yang kedua, model-model dilihat sebagai bahan komposit yang dibina dari lepa dan bata. Kaedah yang kedua membuat anggapan bahawa prisma terdiri daripada bahan komposit dan memberikan ramalan yang lebih tepat bagi pengagihan tegasan dalam prisma dan ramalan kegagalan bahan juga menunjukkan kesesuaian yang baik dengan keputusan ujikaji. Ini menunjukkan bahawa anggapan kaedah pemodelan bahan komposit lebih baik daripada anggapan bahan sejenis. Dalam kajian ini, suatu faktor penggandaan kekuatan telah dicadangkan untuk tujuan rekabentuk yang boleh digunakan untuk menilai keputusan ujikaji kekuatan mampatan batu bata dari keputusan analisis unsur terhingga.

Kata kunci: Pertukangan bata, kesejenisan, komposit, tegasan, keterikan.

1.0 INTRODUCTION

Masonry is a composite material with the brick as the building units and mortar as the joining material, which are bonded together at an interface. The basic mechanical properties of the masonry are strongly influenced by the mechanical properties of its

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constituents that is brick and mortar. Utilizing the material parameters obtained from experiments and using actual geometric details of both components and joints, it is possible to reproduce the behavior of masonry numerically [1]

Equivalent elastic modulus for brick masonry has been studied by Pande [2] assuming that no slippage occurs between the mortar layers and brick unit with the head joints considered to be continuous. The study proved that for a normal case, where elastic modulus of mortar, E_j is less then E_b (elastic modulus of brick), the increase in mortar thickness results in reduction of elastic modulus of the masonry and increase of elastic modulus of mortar leads to an increase in the elastic modulus of masonry . Numerous investigations were performed on homogenization technique, which is based on the assumption that masonry is a periodic structure formed from regular repetition of non-homogeneous elements whose dimensions are small to the overall size of the structure [3,4,5,6]. In this method, behavior of the masonry is roughly approximated by linear elasticity and perfect interface bonding hypothesis.

The main problem in this approach is the mathematical errors introduced in the homogenization process when large difference in stiffness is expected for the two components. Therefore, the accuracy of the homogenized masonry model for an increasing ratio between the stiffness of the two components was assessed by Zucchini et al [7]. They proposed a model and showed that up to a stiffness ratio of one thousand, the maximum error in the calculation of the homogenized Young's moduli is lesser then 5 %.

In order to improve the finite element method (FEM) prediction of the masonry behaviour, micro modeling for small masonry prisms using link elements was proposed by Pande et al [8]. This approach is very accurate and gives good insight into micro stresses in masonry. However the limitation is that such modeling requires large number of elements and input of mechanical characteristics of constituents. To further the studies, the progressive failure in structural masonry was analyzed using a continuum formulation that is applicable to representative volume which comprises large number of units interspersed by mortar joints [9]. Even though, the representation of each unit and joint becomes impractical in case of masonry structure comprising a large number of units, a 3D finite element failure analysis of masonry walls subjected to both vertical and horizontal load was proposed by Subash et al [10]. The wall was modeled using eight-node solid elements and the cracking at the interface was modeled using simple Mohr-coulomb criterion.

In the present study, models with two different material assumptions are presented: in one, both phase of the material is replaced with an equivalent material property assuming it to be a homogenized material; the other treats masonry as a composite material consisting brick set and mortar joint. It proposes a failure criterion for masonry in which the ultimate behavior of masonry is described by the classical linear elastic relation. To demonstrate the applicability of such models, the results of the experimental investigation performed earlier [11] have been compared with the finite element modeling using both models. The tested masonry prisms were in five sets, and each set had a specific mortar joint thickness. Each model was constructed using five clay bricks as shown in Figure.1.

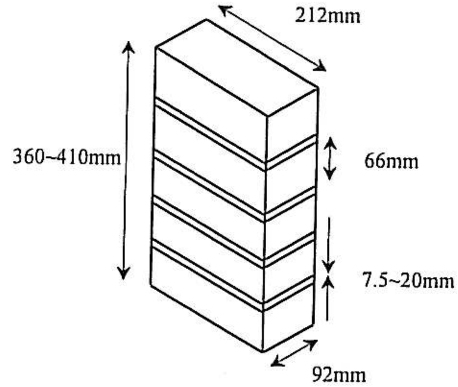

Figure 1: Dimensions of a typical five clay bricks prism

2.0 NUMERICAL ANALYSIS

Using eight-node isoparametric brick element, each model has been discretized into 72 elements. The discretization is such that, bricks and mortar joints have been represented by separate layers of elements as shown in Figure 2.

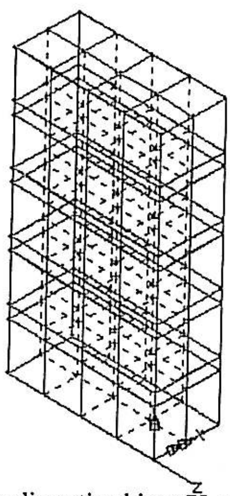

Figure 2: Prism discretized into 72 eight noded brick elements

Each model is assumed to be subjected to axial compressive load as shown in Figure 3. The boundary condition adopted is that all nodes at the base of the models are assumed to be fixed. The models are assumed to be constructed from five local clay bricks having dimensions of 212 mm x 92 mm x 66mm (length x width x height), and each model with unique mortar joint thickness. There are five sets of models having different mortar joint thickness, which are 7.5mm, 10mm, 12.5mm, 15mm and 20.0 mm.

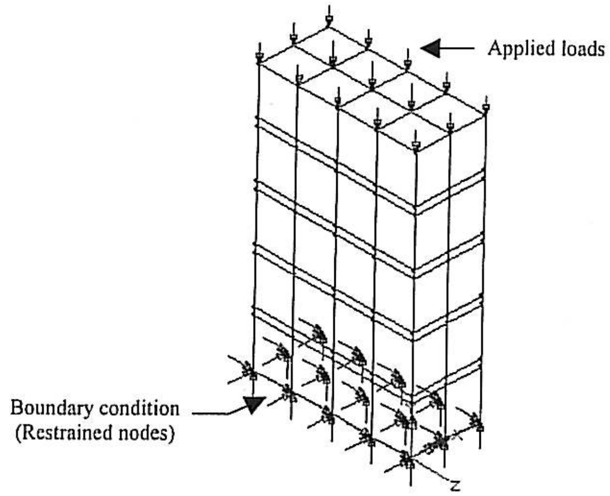

Figure 3: Typical model showing the applied load and boundary conditions

2.1 Analysis of models as a homogenized material

In this analysis the brickwork which is made from two different materials of clay bricks and mortar has been replaced by an equivalent homogenous material. This approach, which is used by many researchers in the field, assumes that brickwork is made from a single material [8]. Determination of the states of strains/stress and also limit states are possible with the aid of finite element analysis, if the material properties of the masonry are properly defined. The equivalent material properties can be determined by experimental method and might require a set of extensive and costly experiments. To overcome this barrier, the experimental method can be replaced with the formulation recommended by Uniform Building Code (UBC-1991) of America. The equation for the elastic properties of the equivalent material is derived in terms of elastic properties of the brick and mortar together with relative thickness [13].

UBC recommends that the modulus elasticity of masonry (E_m) in compression can be calculated using the following equation:

$$E_m = \frac{(1+\gamma_t)}{\left(1+\dfrac{\gamma_t}{\gamma_m}\right)} E_b \qquad \ldots(1)$$

where,

$$\gamma_t = \text{Thickness ratio} = \frac{t_j}{t_b}$$

γ_m = Modulus ratio = $\dfrac{E_j}{E_b}$

t_j = Thickness of mortar joints

t_b = Thickness of brick

E_j = Modulus of elasticity of mortar joints, assumed to be 20000 N/mm^2 [8].

E_b = Modulus of elasticity of bricks, assumed to be 37000 N/mm^2 [8].

Considering a model with a 7.5 mm mortar joint thickness, the modulus of elasticity of masonry can be calculated as follows:

$$\gamma_t = \frac{t_j}{t_b} = \frac{7.5}{66.0} = 0.114$$

$$\gamma_m = \frac{E_j}{E_b} = 0.541$$

$$\frac{\gamma_t}{\gamma_m} = \frac{0.114}{0.541} = 0.211$$

$$E_m = \left(\frac{1+0.114}{1+0.211}\right)37000 = 34046.95 \text{ N/mm}^2$$

Using equation (1), the modulus of elasticity for various models has been calculated and shown in Table 1.

Table 1: Modulus of elasticity of prisms with different mortar joint thickness

No	Mortar joint thickness (mm)	Modulus of Elasticity, E_b(N/mm^2)	Poisson's Ratio
1	7.5	34046.95	0.25
2	10.0	33278.10	0.25
3	12.5	32721.08	0.25
4	15.0	31968.00	0.25
5	20.0	30893.20	0.25

Poisson's ratio of 0.25 for brickwork as recommended by most of the researchers [8,14] has been adopted in the present study.

Using material properties from Table 1 and LUSAS computer software, three-dimensional finite element analyses of different models have been carried out. From the results, only the maximum vertical compressive stresses and maximum vertical compressive strains in the models have been tabulated and shown in Table 2.

Table 2: Finite element results for models idealized as a homogenized material

Mortar joint thickness (mm)	Maximum vertical compressive stress (N/mm^2)	Maximum vertical compressive strain (mm/mm)
7.5	7.89	0.00415
10.0	7.45	0.00405
12.5	7.30	0.00400
15.0	6.42	0.00370
20.0	6.23	0.00320

2.2 Idealization of models as a composite material

In this analysis the model are assumed to be made from two different materials namely clay bricks and mortar [8,15]. The modulus of elasticity of clay brick is assumed to be $E_b = 37000\ N/mm^2$ with a Poisson's ratio of $\nu_b = 0.1$. The modulus of elasticity of mortar is assumed to be $E_j = 20000\ N/mm^2$ and $\nu_j = 0.25$. The mortar is assumed to be having a mix proportion of 1:1:5 (cement : sand : lime). It is also assumed that the brick and mortar are perfectly bonded together. The finite element discretization of the models is carried out in such a manner that mortar joints and bricks are represented by separate layers of elements. The non-linearity considered in the analysis of the model is only material non-linearity. This is because, mortar having lower compressive strength behave as a non-linear material. The 3-D finite element analyses of the models have been carried out and only maximum vertical compressive stresses and maximum vertical compressive strains in the models are represented in Table 3.

Table 3: Finite element results for models idealized as a composite material

Mortar joint thickness (mm)	Maximum vertical compressive stress (N/mm^2)	Maximum vertical compressive strain (mm/mm)
7.5	7.58	0.00413
10.0	7.25	0.00402
12.5	7.13	0.00340
15.0	6.72	0.00330
20.0	6.21	0.00315

3.0 COMPARISON AND DISCUSSION OF RESULTS

Figure 4 shows the deformed shape of a model with 10mm mortar joint thickness, and contours for vertical stresses of the same model are shown in Figure 5. The comparison of stress-strain curves for different models, from both approaches and experimental study are shown in Figure 6 to Figure 10.

It should be pointed out that the numerical results presented above were obtained after several corrections of the constituent's materials data. The first FEM calculation with the mortar, masonry and brick's mechanical properties taken from the experimental study led to big discrepancies between the results from FEM and testing of the prisms with different mortar joint thickness. This confirms that the properties of mortar inside the joints of the masonry prisms were by far different from those, which were exhibited by the mortar samples tested separately. Therefore in the next FEM, the values of the mechanical properties were increased significantly according to previous literature[8]. These results were much closer to the experimental results.

The stress strain curve obtained from both analyses shows that the maximum compressive strength of brickwork is slightly higher for the case of homogenized material than that of the composite material. Homogenized model behaves as one material, that the dispersion of load in the model will be at about 45°. However in the case of models assumed to be made from composite materials, similar dispersion of vertical loads can't be expected. The mortar joint having lower strength than the brick strength which will cause a reduction in the compressive strength of masonry. Actual compressive strength of the masonry determined by experimental method is much higher then the strength obtained by numerical method. However, in reality the brickwork is constructed from two layered materials namely brick and mortar therefore, the idealization of composite material for the analysis should be adopted. Homogenized model exhibits about 4% higher strength than the model assumed as a composite material.

In order to get maximum compressive strength in brickworks, UBC has recommended that the mortar joint thickness should be about 3/8″ (9.52mm). Similarly BS 5628 has also recommended that the mortar joint thickness in brick masonry should be 10mm to get optimum compressive strength. However the earlier experimental study [11] and the present numerical investigation indicate that the maximum compressive strength in brick masonry made from local material can be obtained when the mortar joint thickness is 7.5mm.

The comparison of experimental and numerical results indicates that the compressive strength of masonry obtained by experimental method is 50% higher than those obtained by finite element method. Therefore, to get the actual compressive design strength of brick masonry, the finite element analysis results should be enhanced by a factor of 1.5.

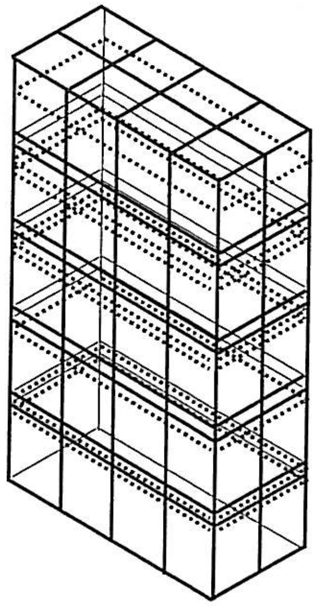

Figure 4: Deformed shape of the model with 10mm mortar joint thickness

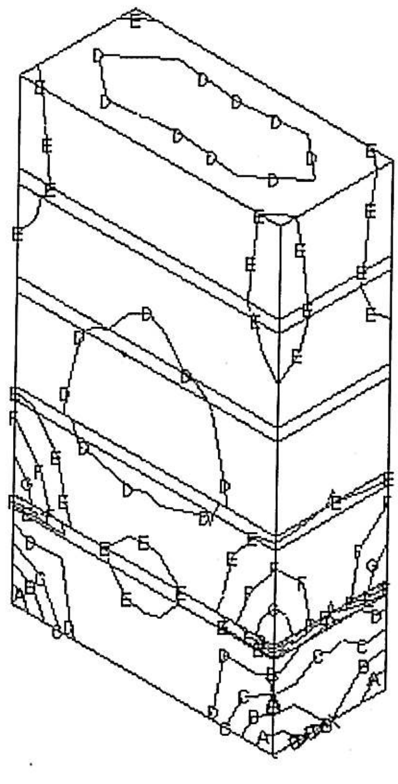

Figure 5: Vertical stress contour in the model with 10mm mortar joint thickness

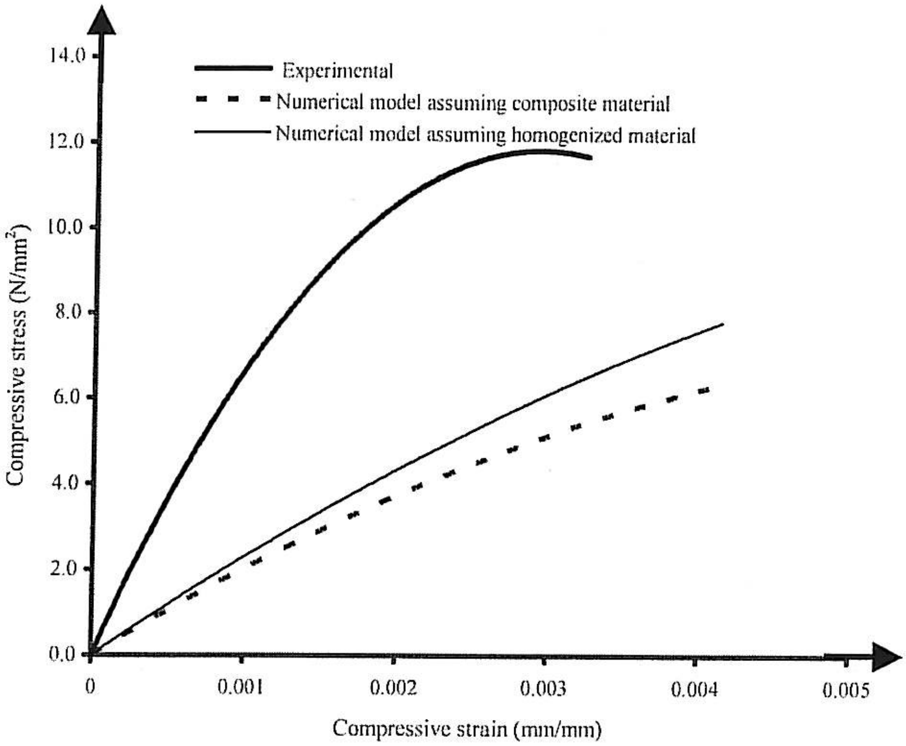

Figure 6: Stress-strain curve for model with 7.5mm mortar joint thickness

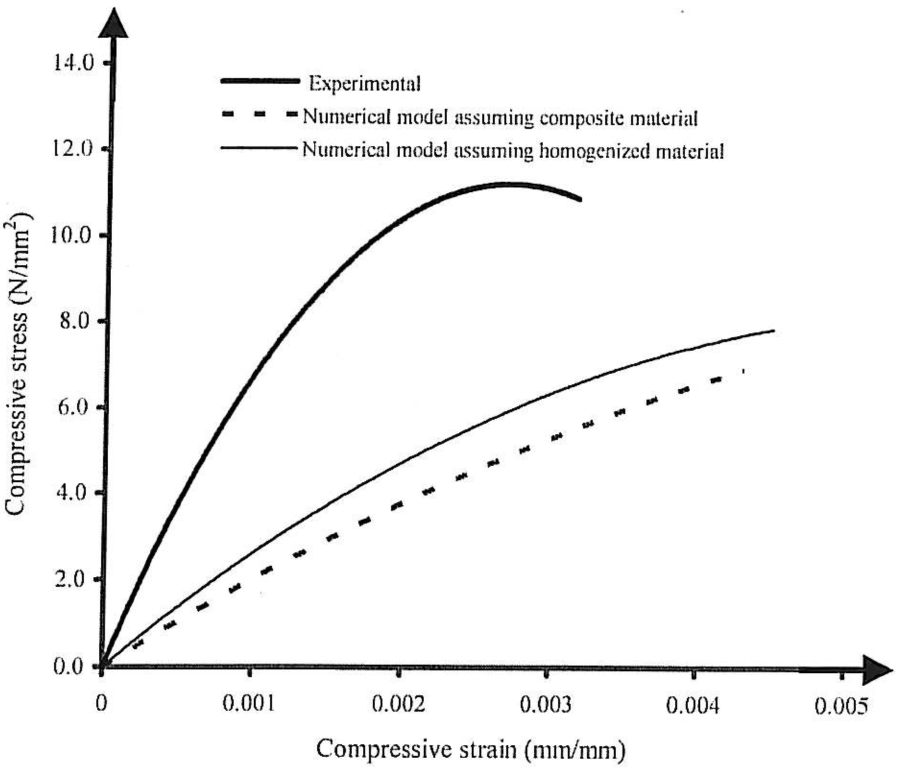

Figure 7: Stress-strain curve for model with 10 mm mortar joint thickness

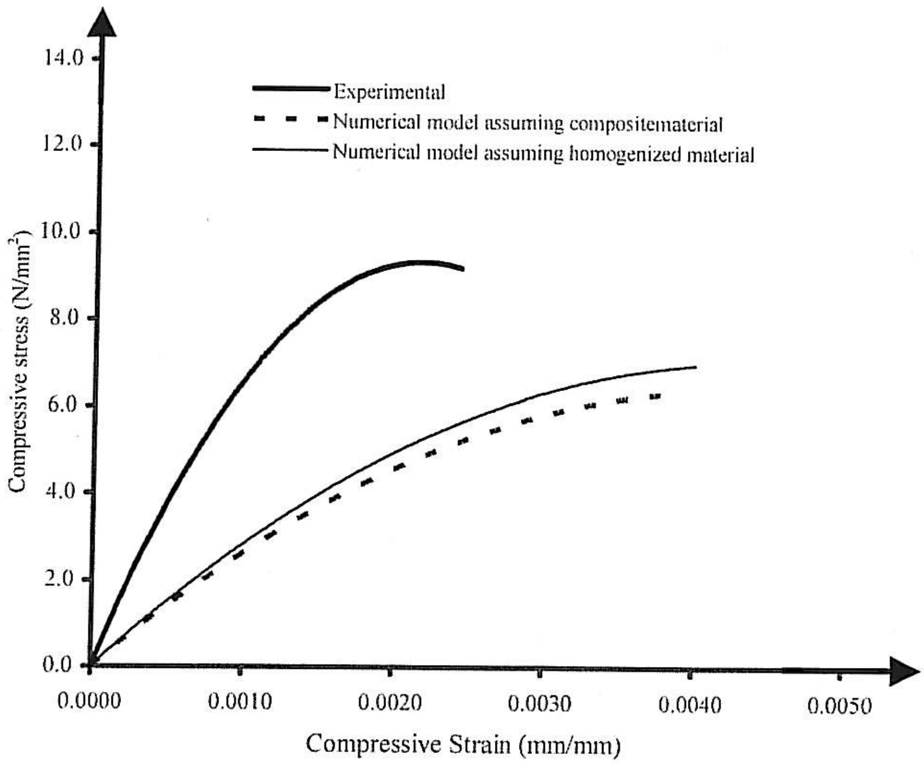

Figure 8: Stress-strain curve for model with 12.5mm mortar joint thickness

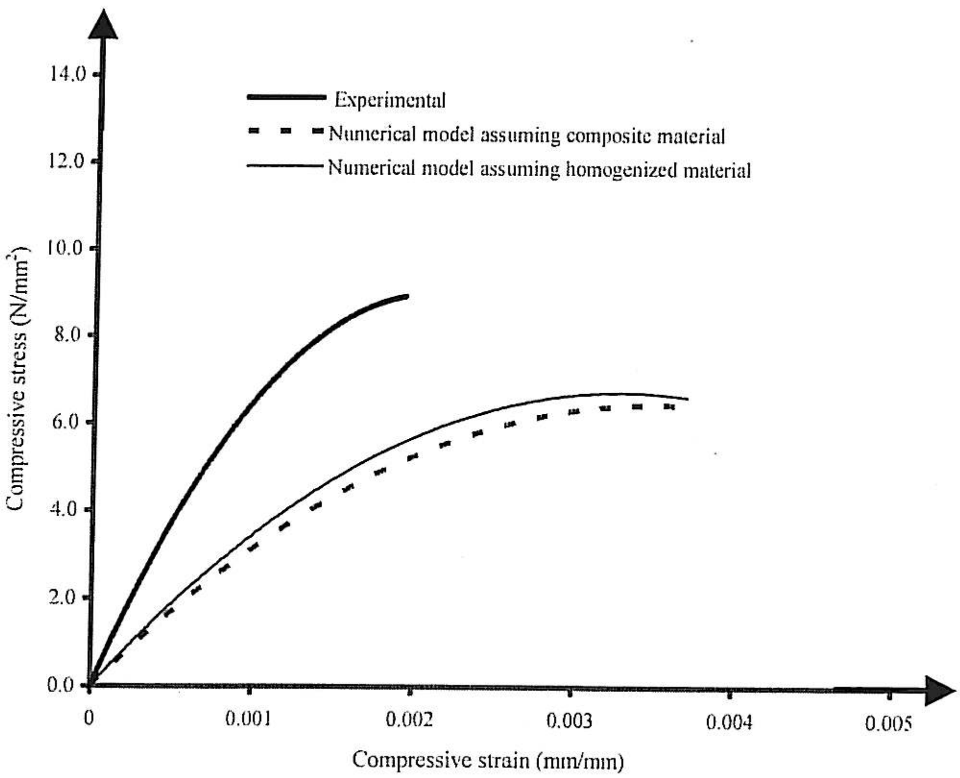

Figure 9: Stress-strain curve for model with 15.0mm mortar joint thickness

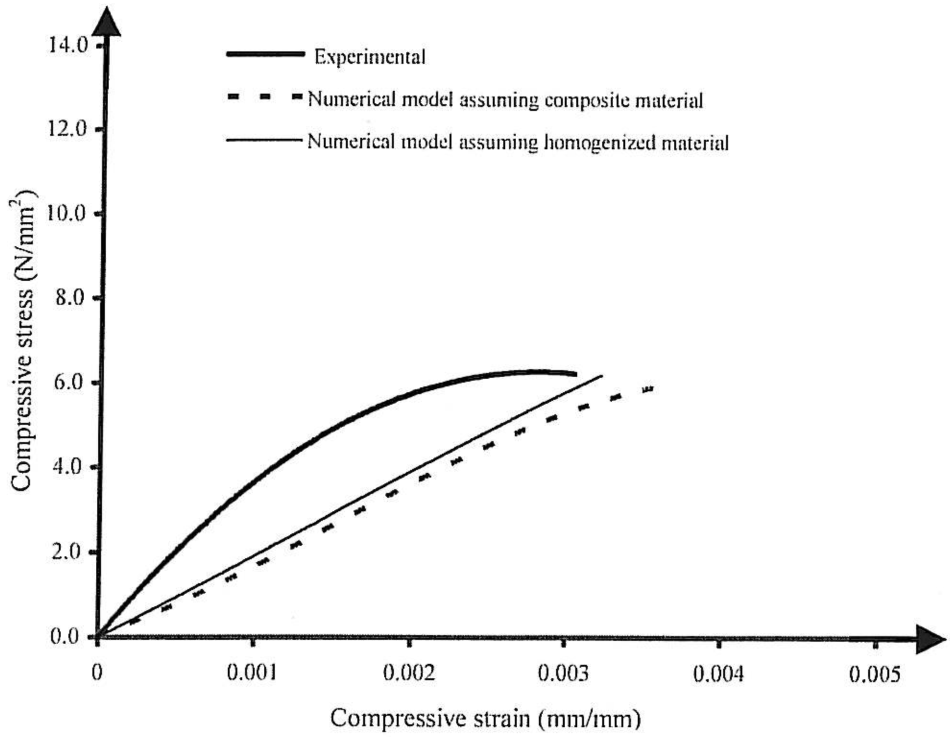

Figure 10: Stress-strain curve for model with 20.0mm mortar joint thickness

4.0 CONCLUSIONS

Numerical and experimental analyses results show that, by increasing the mortar joint thickness, the strength of the masonry will decrease. The maximum compressive strength of models is obtained when the thickness of the mortar joint is 7.5mm.
It is proposed that in idealization for numerical analysis the brickwork should be assumed as a composite material, since brick masonry is in reality a layered material.
For the design purposes, the compressive strength of brick masonry obtained from finite element analysis should be magnified with a minimum factor of 1.5 in order to get the actual strength of the brickwork.

5.0 SCOPE FOR FURTHER RESEARCH

The comparison of the results from present study with that of the experimental investigation carried out earlier, show that there is a significant difference in some cases. Since the experimental result in each set is the average value obtained from the testing of four to five prisms, therefore by testing large number of prisms in each set having a unique mortar joint thickness may give a better average value.

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